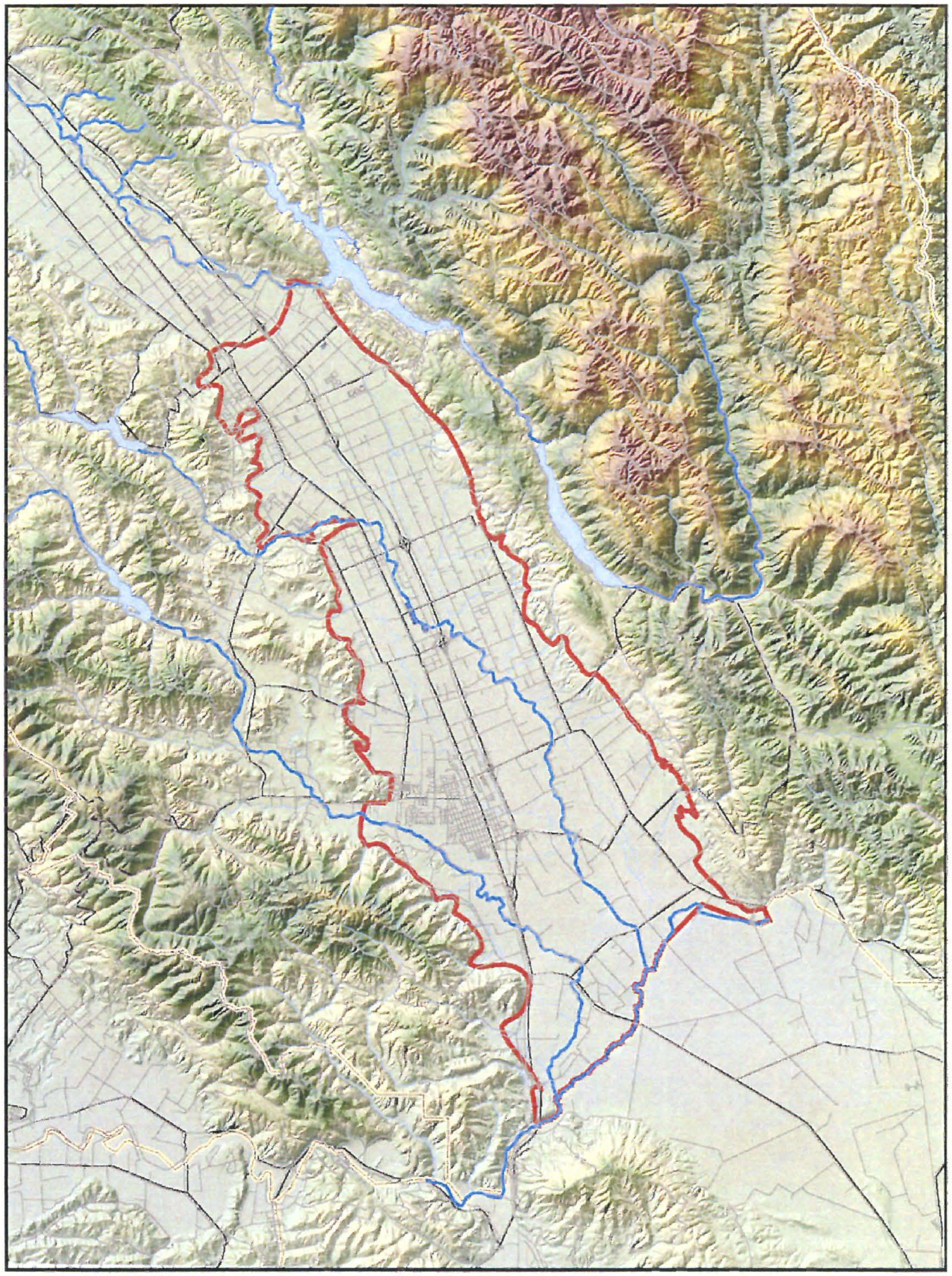
Llagas Basin Numerical Groundwater Model



Prepared for
Santa Clara Valley Water District

Prepared by

CH2MHILL

May 2005

Report

Llagas Basin Numerical Groundwater Model

Prepared for

Santa Clara Valley Water District
5750 Almaden Expressway
San Jose, CA 95118-3686

May 2005

CH2MHILL
155 Grand Ave. Ste. 1000
Oakland, CA 94612

GB1025 S383 L58 2005 c.1

SANTA CLARA VALLEY WATER DISTRICT
LIBRARY
5750 ALMADEN EXPRESSWAY
SAN JOSE, CALIFORNIA 95118

Report

Llagas Basin Numerical Groundwater Model

Submitted to

Santa Clara Valley Water District

May 2005

Copyright 2005 by CH2M HILL, Inc.

Reproduction and distribution in whole or in part beyond the intended scope of the contract without the written consent of CH2M HILL, Inc. is prohibited.

Llagas Basin Numerical Groundwater Model Report

A numerical groundwater model represents an actual physical system through numerous simplifying assumptions. These assumptions are related, in part, to the size of the area being modeled and the density and quality of available data. Models are typically constructed with particular purposes and objectives in mind that account for these and other relevant factors.

The Llagas Basin Groundwater Model was developed as a tool to help Santa Clara Valley Water District (District) better manage the Llagas Basin groundwater resource on a basinwide scale, including maximizing basin yield under specified constraints and conditions. It is CH2M HILL's opinion that the Llagas Basin Groundwater Model will provide the District with an exceptionally useful tool for these purposes, and will greatly aid them in assessing and comparing affects of various basinwide management strategies. For example, the model could be used to support "programmatic-level" evaluations of potential environmental impacts associated with changes in the location and amount of recharge and pumpage from the basin. Although any given simulation may not be entirely accurate, differences between scenarios provide useful information about system tendencies under varied stress conditions.

The model will generally prove less useful for assessment of small-scale local issues, such as detailed assessment of contaminant transport at particular release sites. This is because high concentrations of contaminants in an alluvial system tend to travel in relatively narrow (tens of feet), thin (often 10 feet or less) high-conductivity zones. The existing basinwide model represents average conditions over 500-foot-square blocks that are as much as 100 feet thick. Even if the model grid were refined to a scale of tens of feet, aquifer property and other data are still averaged into 500-foot-square blocks. More detailed analysis would require more densely populated data sets to characterize the heterogeneity of the natural system at this finer scale.

The Llagas Basin Groundwater Model was developed based on existing reports and data provided by the District as of January 2004. Field investigations were not conducted as part of this work effort. Certain field investigations could improve the conceptual understanding of the basin, lead to better model calibration, and provide a more reliable modeling tool. These recommendations are presented herein.

Contents

Executive Summary ES-1
- ES.1 Background ES-1
- ES.2 Conceptual Model Refinement ES-1
- ES.3 Numerical Model Development ES-2
- ES.4 Model Calibration ES-2
  - ES.4.1 Uncertainty Analysis ES-3
  - ES.4.2 Recommendations ES-3

1.0 Conceptual Model 1-1
- 1.1 Introduction 1-1
- 1.2 Basin Description 1-1
  - 1.2.1 Physiography 1-1
  - 1.2.2 Climate 1-2
  - 1.2.3 Land Use 1-2
- 1.3 Hydrogeology 1-2
  - 1.3.1 Hydrogeology of the Llagas Basin 1-3
  - 1.3.2 Hydrostratigraphic Units 1-3
  - 1.3.3 Hydrogeologic Properties and Well Yield 1-4
  - 1.3.4 Water Levels 1-6
- 1.4 Water Budget 1-6
  - 1.4.1 Recharge 1-7
  - 1.4.2 Discharge 1-9

2.0 Numerical Model Development 2-1
- 2.1 Introduction 2-1
- 2.2 Model Grid 2-1
- 2.3 Hydrogeologic Properties 2-1
- 2.4 Steady-state and Initial Conditions 2-2
- 2.5 Model Fluxes and Boundaries 2-2
  - 2.5.1 Deep Percolation of Precipitation and Water Applied for Agricultural Irrigation 2-3
  - 2.5.2 Intentional Recharge to Creeks and Ponds 2-3
  - 2.5.3 Subsurface Inflow from Bedrock Uplands and Alluvial Tributary Canyons 2-3
  - 2.5.4 Pajaro River 2-3
  - 2.5.5 Stream Seepage 2-3
  - 2.5.6 Lateral Boundaries 2-3
  - 2.5.7 Pumping 2-4

3.0 Model Calibration 3-1
- 3.1 Introduction 3-1
- 3.2 Calibration Methods 3-1
  - 3.2.1 Steady-state Calibration 3-1
  - 3.2.2 Transient Calibration 3-1
- 3.3 Uncertainty Analysis 3-6

3.3.1 Scenario 1: Redistribute Subsurface Inflow 3-6
3.3.2 Scenario 2: Decrease Areal Recharge by 25 Percent 3-7
3.4 Recommendations 3-8
4.0 References 4-1

Tables

1-1 Transmissivity Estimated from Specific Capacity Data and Aquifer Tests 1-5

2-1 Fraction of Annual Pumping Based on Agricultural Demand Estimates 2-4

3-1a Model Parameters Changed During Manual Calibration 3-3

3-1b Model Parameters Changed During Automated Inverse Calibration (PEST) 3-4

Figures

ES-1 General Location Map

ES-2 Model Grid (500 x 500)

ES-3 Monitoring Wells Used During Calibration

ES-4 Calibration Hydrographs

ES-5 Residual Statistics

ES-6 Final and Alternative Calibration Hydrographs—Scenario 1

ES-7 Final and Alternative Calibration Hydrographs—Scenario 2

ES-8 Transmissivity Distribution (gpd/ft)—Final and Alternative Calibrations (Scenario 1)

ES-9 Transmissivity Distribution (gpd/ft)—Final and Alternative Calibrations (Scenario 2)

1-1 General Location Map

1-2 Topography

1-3 Rain Gage Locations

1-4 Precipitation Data and Climatic Trends

1-5 Mean Annual Precipitation for 100 Years of Historical Data

1-6a Land Use 1990

1-6b Land Use 1998

1-7 Land Use Trends

1-8 Surficial Geology

1-9 Cross Section Location Map

1-10 Cross Section A-A′

1-11 Cross Section B-B′

1-12 Cross Section C-C′

1-13 Cross Section D-D′

1-14 Cross Section E-E′

1-15 Cross Section F-F′

1-16 Cross Section G-G′

1-17 Cross Section H-H′

1-18 Cross Section I-I′

1-19 Cross Section J-J′

1-20 Cross Section K-K′

1-21 Cross Section L-L′

1-22 Cross Section M-M′

1-23 Cross Section N-N′

1-24 Cross Section O-O′

1-25 Cross Section P-P′

1-26 Cross Section Q-Q′

1-27 Cross Section R-R′

1-28 Cross Section S-S′

1-29 Cross Section T-T′

1-30 Cross Section U-U′

1-31 Cross Section V-V′

1-32 Bedrock Elevation

1-33 Saturated Thickness (Steady-state Period 1996-98)

1-34 Saturated Thickness (Low Water Level Period 1989-1990)

1-35 Hydraulic Conductivity (Estimated from Specific Capacity)

1-36 Transmissivity (Estimated from Specific Capacity)

1-37 Location of Wells with Water Level Data

1-38 Hydrographs (All Wells)

1-39 Hydrographs (09S02E)
1-40 Hydrographs (09S03E)
1-41 Hydrographs (10S03E)
1-42 Hydrographs (10S04E)
1-43 Hydrographs (11S04E)
1-44 Long Term Hydrographs and Climatic Trends
1-45 Steady-state Water Levels (1996-98)
1-46 Low Water Levels (1989-90)
1-47 Water Level Difference Map (Steady-state - Low)
1-48 Hydrographs of Wells with Screen Data
1-49 Water Budget Summary
1-50 Pond and Creek Recharge Facilities
1-51 Pond Recharge Summary
1-52 Streambed Recharge Summary
1-53 Location of Spreader Dams
1-54 Location of Streambed Recharge Capacities
1-55 Pumping Summary
2-1 Model Grid (500 x 500)
2-2 Production Well Perforations With Depth—09S03E Wells (36 Wells)
2-3 Production Well Perforations With Depth—10S03E Wells (108 Wells)
2-4 Production Well Perforations With Depth—09S04E Wells (54 Wells)
2-5 Production Well Perforations With Depth—11S04E Wells (59 Wells)
2-6 Cross Section Locations
2-7 Cross Section C-C′
2-8 Cross Section D-D′
2-9 Hydraulic Conductivity (ft/d)—Distribution Layer-1
2-10 Hydraulic Conductivity (ft/d)—Distribution Layer-2
2-11 Hydraulic Conductivity (ft/d)—Distribution Layer-3
2-12 Hydraulic Conductivity (ft/d)—Distribution Layer-4
2-13 Steady-state Water Level Targets—Water Years 1996-1998

2-14 Initial Conditions Water Level Map for Transient Simulation—Water Year 1988

2-15 Location of Wells Used to Simulate Intentional Recharge

2-16 Location of Wells Used to Simulate Subsurface Inflow

2-17 Pajaro River and Stream Seepage

2-18 General Head Boundary

2-19 Pumping Wells

3-1 Monitoring Wells Used During Calibration

3-2 Calibration Hydrographs

3-3 Residual Statistics

3-4 Llagas Basin Maximum Perchlorate Concentrations—November 10, 1999 to March 18, 2004

3-5 Particle Tracking

3-6 Simulated Water Budget Components

3-7 SCVWD Draft Conceptual Water Budget and Average Simulated Water Budget (1990-2001)

3-8 Hydraulic Conductivity Distribution (ft/d)—Layers 1 through 4

3-9 Transmissivity Distribution (gpd/ft)—Final Calibration

3-10 Available Specific Capacity (gpm/ft)

3-11 Specific Yield Distribution Layer-1

3-12 Simulated Average Recharge Distribution

3-13 Final and Alternative Calibration Hydrographs—Scenario 1

3-14 Final and Alternative Residual Statistics—Scenario 1

3-15 Transmissivity Distribution (gpd/ft)—Final and Alternative Calibrations (Scenario 1)

3-16 Simulation of Perchlorate in Groundwater

3-17 Final and Alternative Calibration Hydrographs—Scenario 2

3-18 Final and Alternative Residual Statistics—Scenario 2

3-19 Transmissivity Distribution (gpd/ft)—Final and Alternative Calibrations (Scenario 2)

3-20 Discharge to Creeks—Final and Alternative Calibrations

Appendices

A	Pumping Well Database and Algorithm
B	Summary of Files Used for Modeling
C	Calibration Hydrographs
D	Alternative Calibration

EXECUTIVE SUMMARY

Executive Summary

ES.1 Background

CH2M HILL developed a groundwater model of the Llagas Basin for the Santa Clara Valley Water District (District). The purpose of the model is to provide District staff with a tool to support development and management of the local groundwater resource. Work involved with development of the model included refining the District's conceptual model of the basin to facilitate development of the numerical model, converting the conceptual model to the numerical model, calibrating the numerical model, and performing uncertainty analysis using inverse modeling techniques. Results of this work were originally presented to the District in the following technical memorandums:

- *Llagas Basin Conceptual Model Review* (CH2M HILL, 2004a)
- *Development of the Llagas Numerical Model* (CH2M HILL, 2004b)
- *Llagas Numerical Model Calibration* (CH2M HILL, 2005)

These technical memorandums are reproduced in this report as individual chapters with generally minor modifications. A copy of the electronic files developed during the project and a brief explanation of how these files are used is included as part of this report.

ES.2 Conceptual Model Refinement

Llagas Basin is one of three interconnected groundwater basins located in south Santa Clara County (Figure ES-1). The basin is a northwest-southeast trending alluvial valley that extends from the boundary with Coyote Basin (a tributary basin to Santa Clara Valley) about 14 miles southeast to the Pajaro River and the boundary with San Benito County. It covers an area of about 67 square miles.

Principal water-bearing sediments in the Llagas Basin consist primarily of Holocene age alluvial fan deposits, young and old alluvium, and stream deposits. The alluvium is as much as 500 feet thick in the southern portion of the basin, and consists of poorly consolidated to unconsolidated deposits of clay, silt, sand, and gravel.

Water budget data for the Llagas Basin are available from 1988 to 2002. Some data are available via direct measurement (e.g., precipitation via rain gage, or pan evaporation). Other data are more difficult to quantify. Primary sources of recharge to the Llagas Basin include intentional recharge to creeks and ponds, deep percolation of water applied for agricultural irrigation and precipitation, subsurface inflow from bedrock uplands and alluvial tributary canyons, and stream seepage. A lesser source of water to the basin is deep percolation of water applied for landscape irrigation (e.g., septic system). Sources of discharge from the Llagas Basin include groundwater pumpage, underflow across the southern boundary to the Bolsa Basin, discharge to Pajaro River, discharge to Llagas and Uvas Creeks, and low-lying swales and irrigation ditches (drains).

ES.3 Numerical Model Development

The boundaries of the model grid encompass the main alluvial areas of Llagas Valley. The model contains four active layers of uniform 500-foot squares in the X and Y directions corresponding to 122,000 model cells, of which 26,049 are active (Figure ES-2). Results of the conceptual model review indicate an absence of basin-wide hydrostratigraphic layering; accordingly, for modeling purposes, the basin was subdivided into four parallel layers that roughly coincide with distribution of production-well perforations. The bottom of Layer-1 is below the lowest water levels anticipated during simulations, and the bottom of Layer-4 is bedrock interpreted from cross sections.

The model contains numerous flux parameters, including: deep percolation of precipitation and water applied for irrigation, intentional recharge to creeks and ponds, subsurface inflow from bedrock uplands and alluvial tributary canyons, stream seepage, and agricultural, domestic, and municipal pumping. Fluxes within the model are based on a 15-year period of water budget components developed in the draft conceptual model. Fluxes in and out of the model are simulated using various boundary conditions.

ES.4 Model Calibration

Model calibration consisted of both manual and automated inverse techniques. There are two sets of primary calibration targets:

- Transient water levels - observed head data covering the entire 15-year span of historical calibration from 40 calibration wells and flow direction
- Water budget – flow to and from creeks and rivers, flow to drains, and subsurface flow from and to Bolsa Basin

Select calibration hydrographs showing the relationship of observed and computed heads are shown in Figures ES-3 and ES-4. Overall, simulated groundwater levels follow trends in observed groundwater levels and the magnitude of groundwater level rises and declines are generally preserved. A plot of observed versus simulated water levels for all wells with water level data in the basin also suggest good correlation among residuals (Figure ES-5).

Values of specific yield in model Layer-1 range from 0.005 to 0.01 and specific storage for model layers Layer-2 through Layer-4 are assigned a uniform value of 2E-05. Values of specific yield are lower than what is typical for an unconfined aquifer system. To address this issue, an alternative concept was developed, which assumes Llagas Creek recharges groundwater in winter months during excessively wet periods similar to those experienced in the basin during the mid-1990s. Using this concept, specific yield in Layer-1 was increased to 10 percent while long-term water level trends were preserved. Use of the higher value of specific yield is more appropriate for predicting long-term (year or more) basin response. The smaller values are appropriate for simulating shorter-term (six months or less) events like pumping tests or seasonal responses.

ES.4.1 Uncertainty Analysis

Using PEST, two alternative calibrations were developed to assess model uncertainty and evaluate model limitations. The two calibration alternatives were developed based on uncertainty of the recharge water budget components estimated during conceptual model development. Based on the relative uncertainty with the quantity, timing, and spatial distribution of these water budget components, the following scenarios were developed for uncertainty analysis:

Scenario 1 - Subsurface inflow along the eastern margin of the model was eliminated and added to inflow along the western margin.

Scenario 2 – Deep percolation of precipitation and water applied for agricultural irrigation was reduced by 25 percent.

For each scenario, the model was equally well-calibrated using PEST. Hydrographs showing the relationship of observed and computed heads under the new calibrations appear to be very similar or the same as the hydrographs presented for the final calibration (Figures ES-6 and ES-7). The transmissivity distribution does not change sharply either for Scenario-1 (Figure ES-8). Transmissivity changed significantly under Scenario-2 (Figure ES-9) although the range of values for transmissivity remains consistent with observed specific capacity data for the basin and the final calibration transmissivity distribution.

In both cases, despite having equally well calibrated models, the models differ in their predictive capabilities. In Scenario-1 the impact of redistributing subsurface inflow is manifested in the model's prediction of perchlorate migration in groundwater. The final calibration more closely mimics observed perchlorate distribution. In Scenario-2, less groundwater discharges to Llagas and Uvas Creeks and the Pajaro River than in the final calibrated model.

ES.4.2 Recommendations

Development and calibration of a numerical model provides useful insight into areas of the underlying conceptual model that require additional data, and often sheds light onto physical processes occurring in the basin that were not previously understood. Following model development, calibration, and uncertainty analysis, a number of data gaps were identified for the Llagas Basin. Addressing these data gaps will improve the conceptual understanding of the basin, lead to a better model calibration, and provide a more robust predictive tool for managing this groundwater resource from both a quantity and quality perspective. Based on the recent modeling effort it is recommended the District complete the following tasks:

1. **Install monitoring well clusters at select locations in the basin.** Vertical gradients play an important role in contaminant migration and intentional recharge operations in the basin. The current model calibration relied on water level data from 40 monitoring wells. Construction data were available for only five of these wells and they were constructed with relatively long screen intervals (100 to 600 feet). Therefore, vertical gradients may not be accurately represented in the current version of the model. Cluster wells should be monitored at frequent intervals throughout the year so that seasonal changes in the vertical gradients in the basin can be identified.

2. **Install and collect stream stage and flow data from paired gages on Llagas Creek, Uvas Creek, and the Pajaro River.** The District desires to use the model to evaluate current and future intentional recharge practices. Though the current model version uses the River (RIV) package as a source of groundwater discharge, adequate observed streamflow and stage data were not available to be used as a calibration target. In addition, there were no data available on whether the creeks act as a source of groundwater recharge to the basin. Accordingly, gage data should be collected from multiple stream reaches on a regular basis to help quantify the volume and timing of water being recharged to or discharged from the groundwater system in any given location along the streams.
3. **Acquire and update land use data for the basin on an annual or semi-annual basis.** On average, deep percolation from precipitation, water applied for agricultural irrigation, water applied for landscape irrigation, and urban recharge account for over 25 percent of the basin's recharge but can be as high as 65 percent during winter stress periods. Each of these water budget components is directly influenced by land use in the basin. As land use changes over time the rates and distribution of recharge will also need to change.
4. **Perform aquifer tests on existing production wells.** Aquifer test data are not available for existing production wells in the basin. Transmissivity was estimated from available specific capacity data. Aquifer test data from production wells in these areas would provide a better estimate and calibration target for aquifer properties.
5. **Install and test as many as four test wells.** Very few data exist on vertical anisotropy (the ratio of vertical to horizontal hydraulic conductivity, K_v:K_h) in the basin. Vertical anisotropy is important to understanding vertical groundwater leakage. The rates and locations of vertical leakage may have a significant impact on groundwater flow. Currently, the model uses a K_v:K_h ratio of 1:100, but as demonstrated in the uncertainty analysis, the model may be calibrated with a ratio of 1:10. The difference may impact such predictions as discharge to and recharge from creeks and migration of perchlorate. To evaluate vertical anisotropy, it is recommended that as many as four test wells be installed near the monitoring well clusters outlined in the first recommendation.
6. **Conduct a feasibility review for a water quality sampling program.** Water quality data collected on a consistent basis from depth discrete (screen lengths less than 20 feet) monitoring wells are not available. Detailed water quality data may help manage the basin from a water quality perspective and more adequately identify groundwater flow patterns. It is recommended that a feasibility study be performed to evaluate the benefits of establishing a water quality monitoring program.

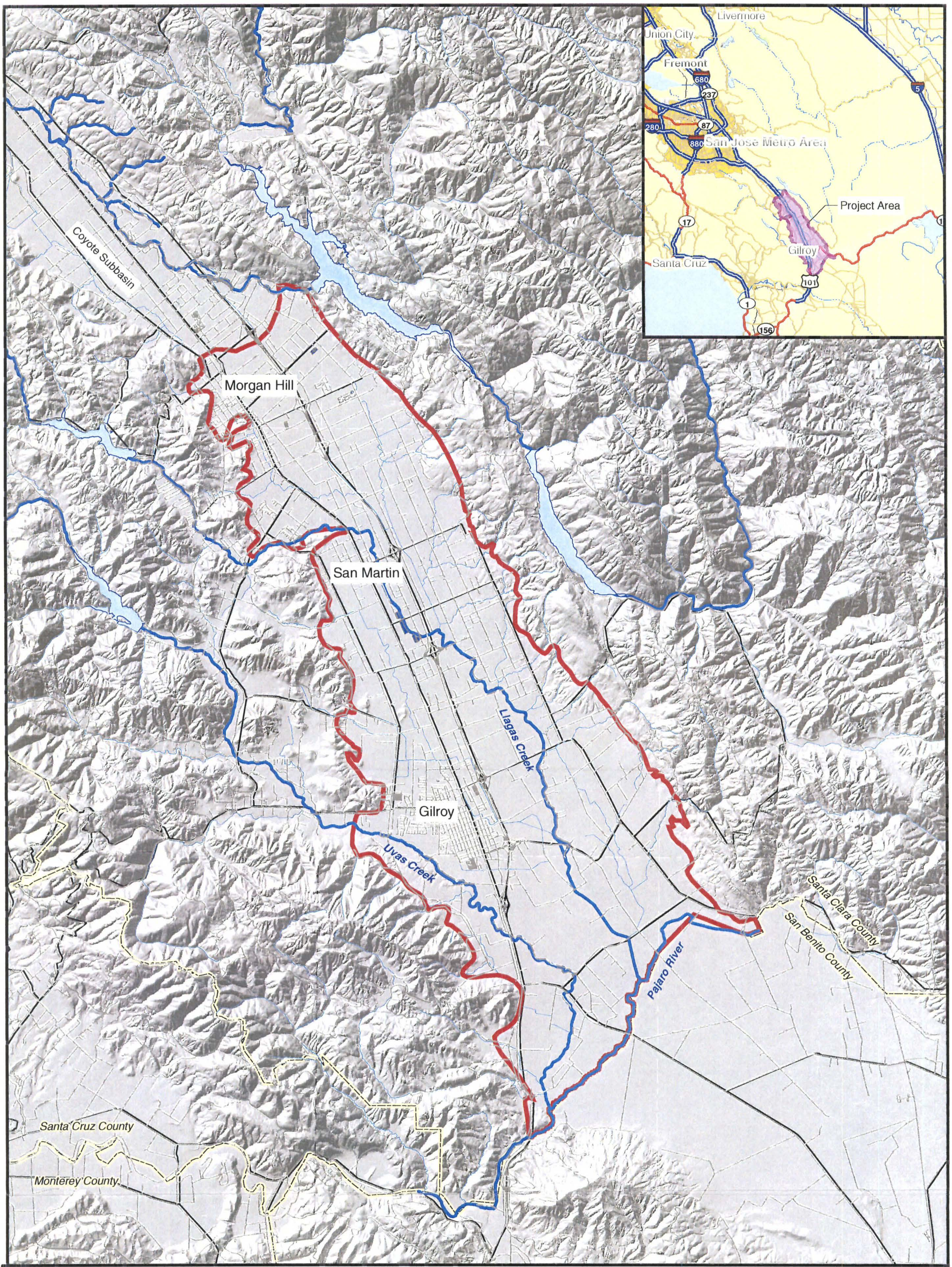


FIGURE ES-1
GENERAL LOCATION MAP
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

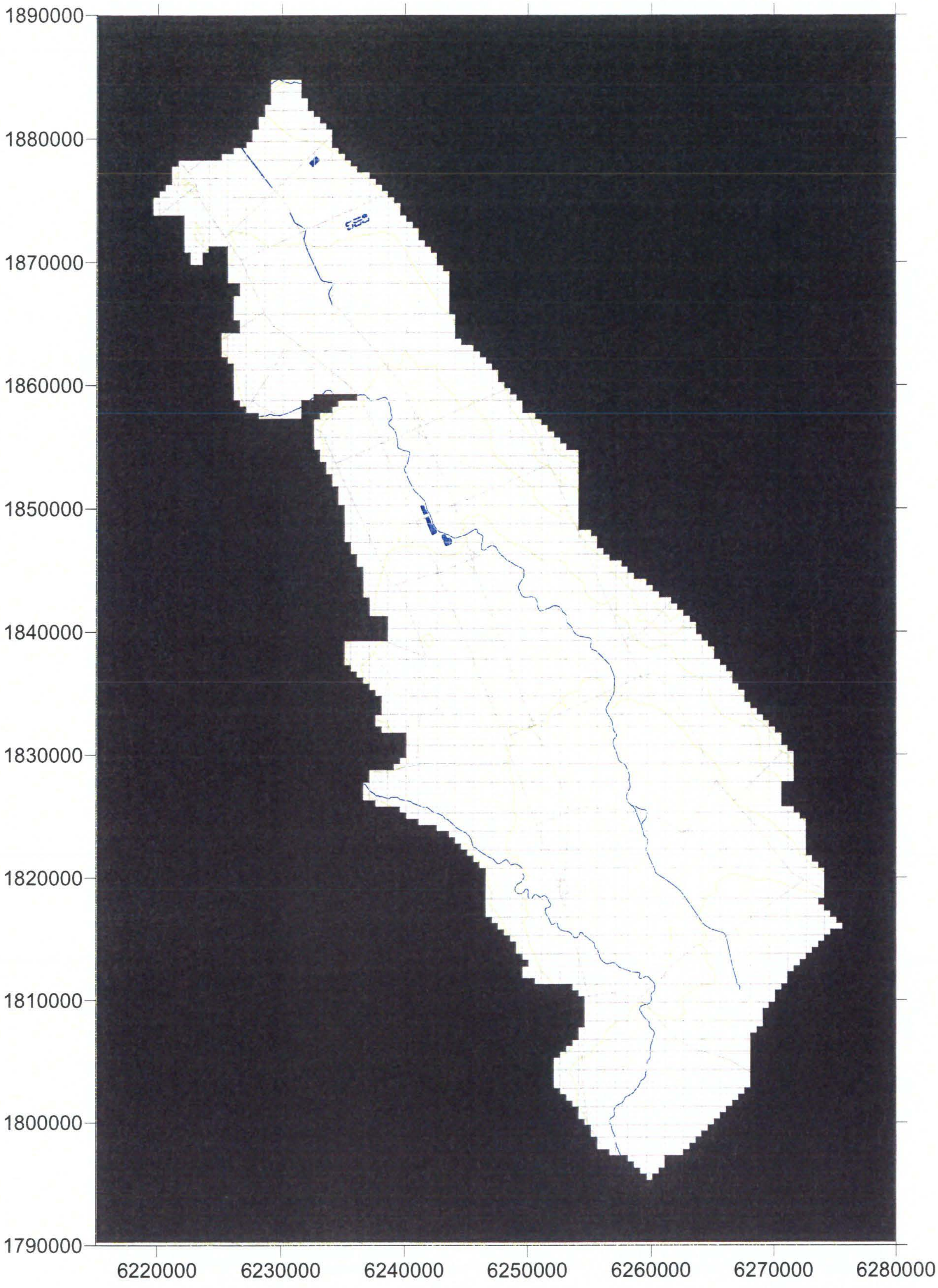
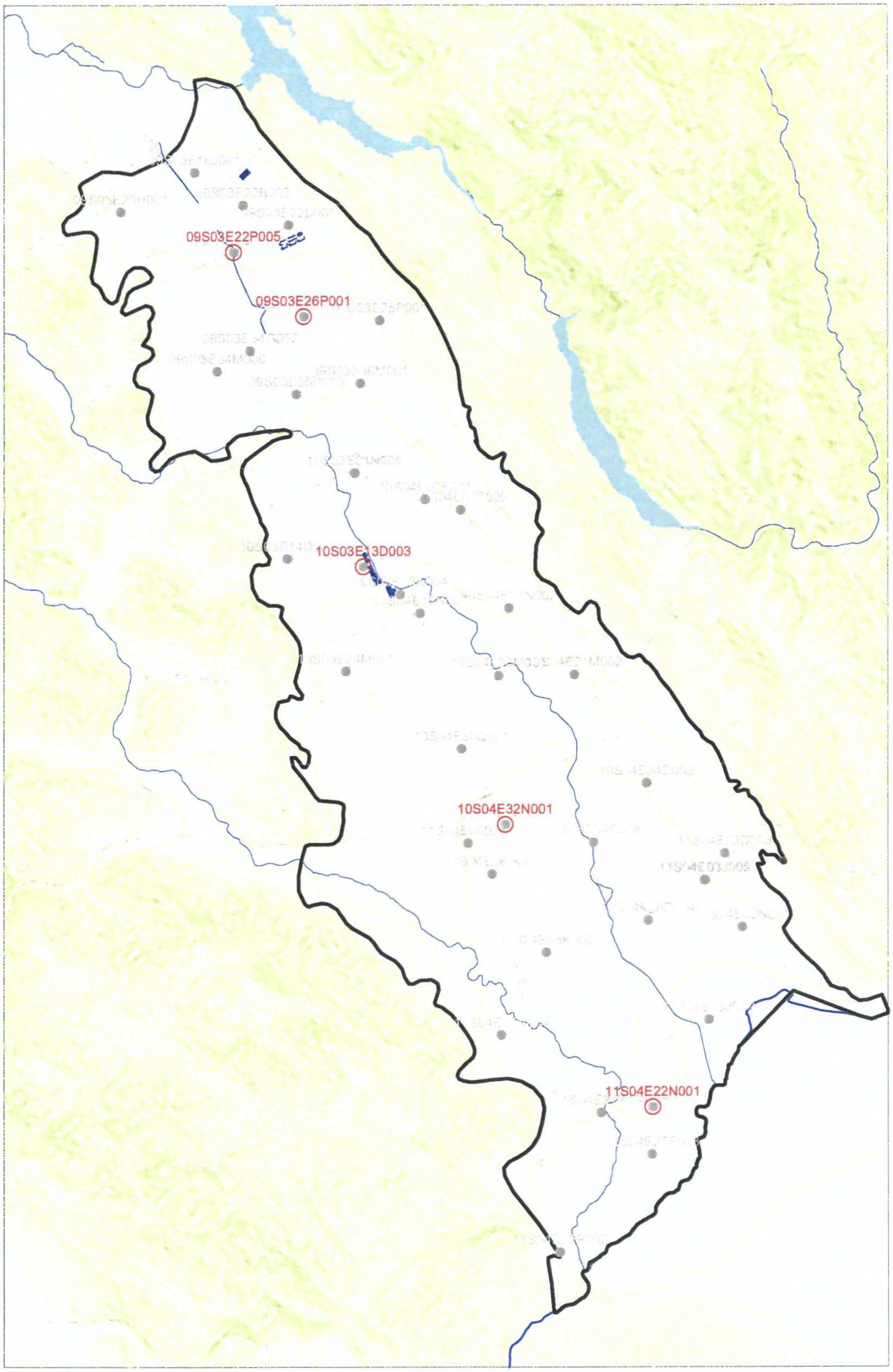


FIGURE ES-2
MODEL GRID (500 X 500)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409.LB.05_Fig 2-1__5/12/05_ccc_sfo

CH2MHILL



● Calibration Well

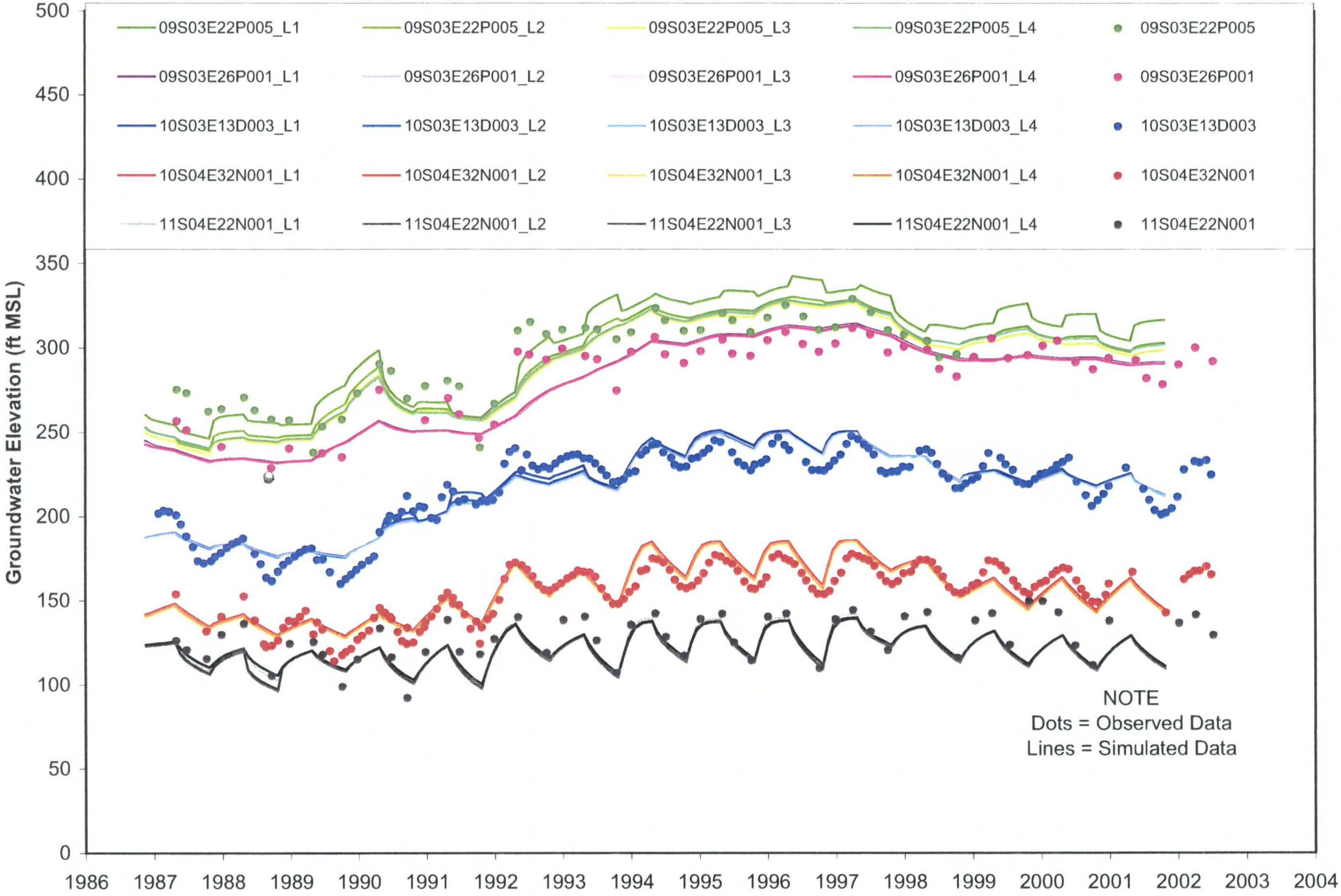
◎ Select Calibration Wells Discussed In Report

FIGURE ES-3
MONITORING WELLS USED DURING CALIBRATION

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 3-1__5/13/05_ccc_sfo

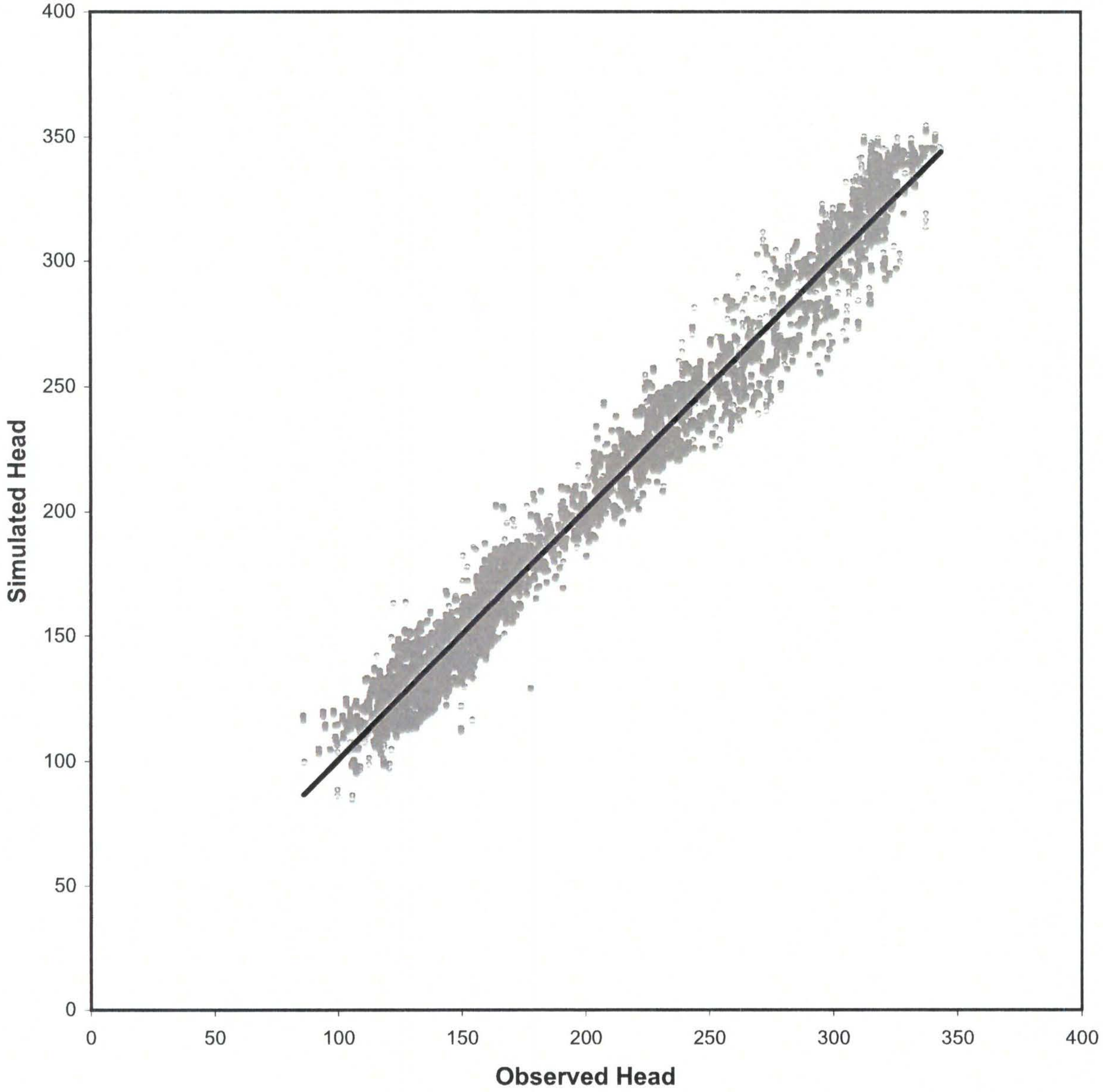


R133 Results.xls

FIGURE ES-4
CALIBRATION HYDROGRAPHS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 3-2__5/13/05_ccc_sfo



$R^2 = 0.9696$

RMS/Range = 4.4%

Residual Mean = -0.3

Absolute Residual Mean = 8.9

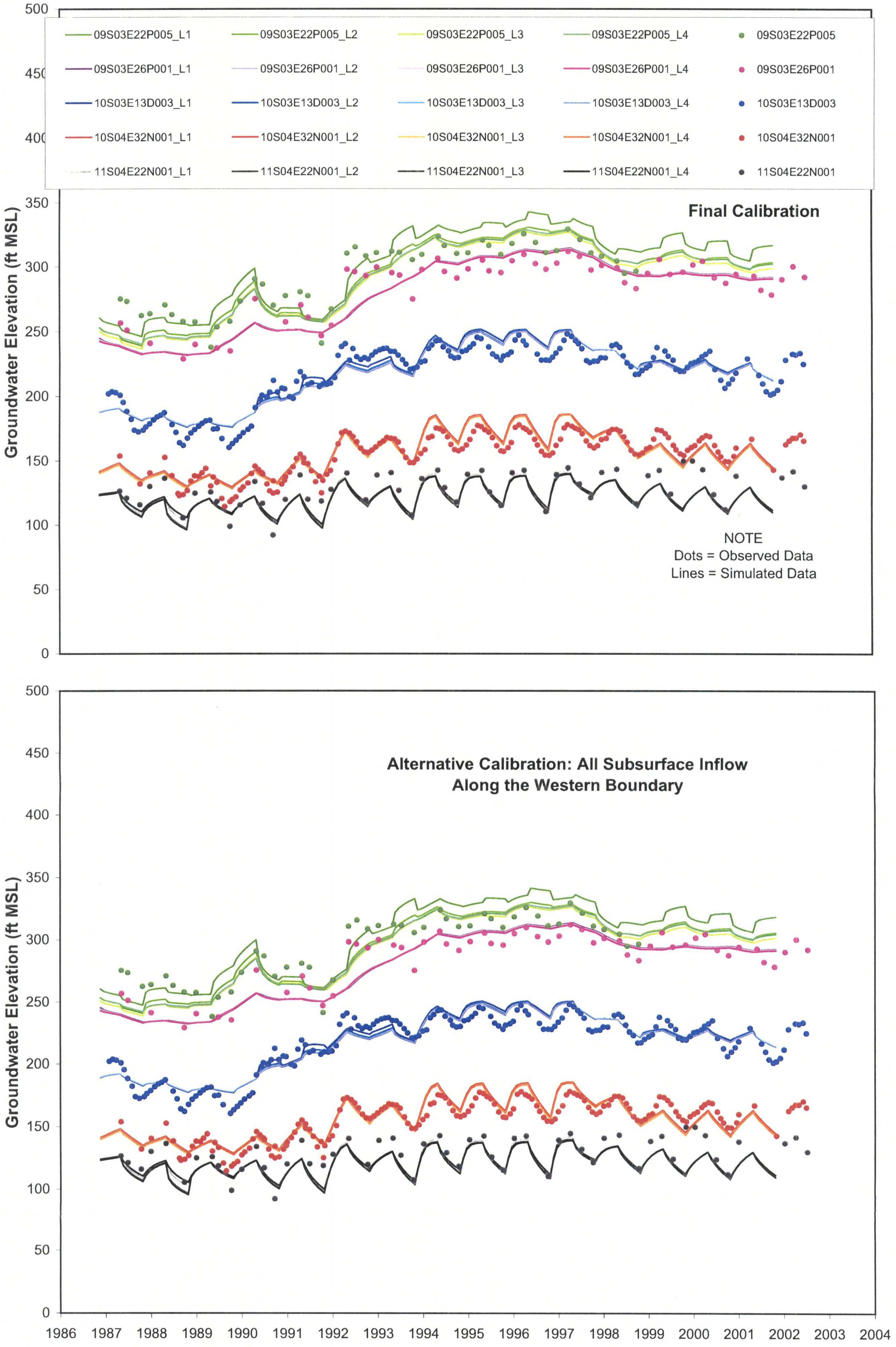
R133Stats.xls

FIGURE ES-5
RESIDUAL STATISTICS

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

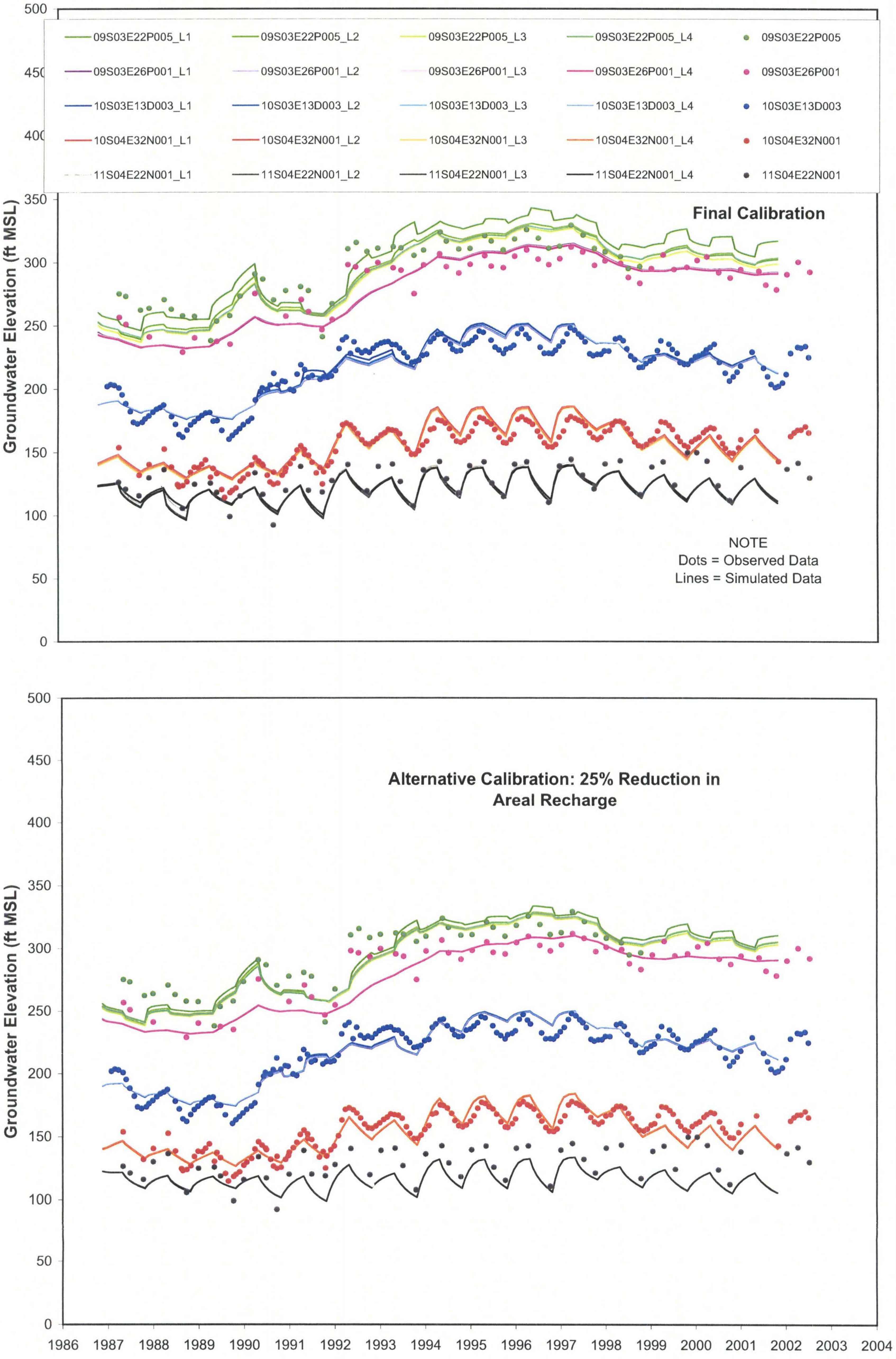
CH2MHILL

188409.LB.05_Fig 3-3__5/13/05_ccc_sfo



ComparisonFigsv2.xls

FIGURE ES-6
FINAL AND ALTERNATIVE
CALIBRATION HYDROGRAPHS
SCENARIO 1
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT



ComparisonFigsv2.xls

FIGURE ES-7
FINAL AND ALTERNATIVE
CALIBRATION HYDROGRAPHS
SCENARIO 2
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

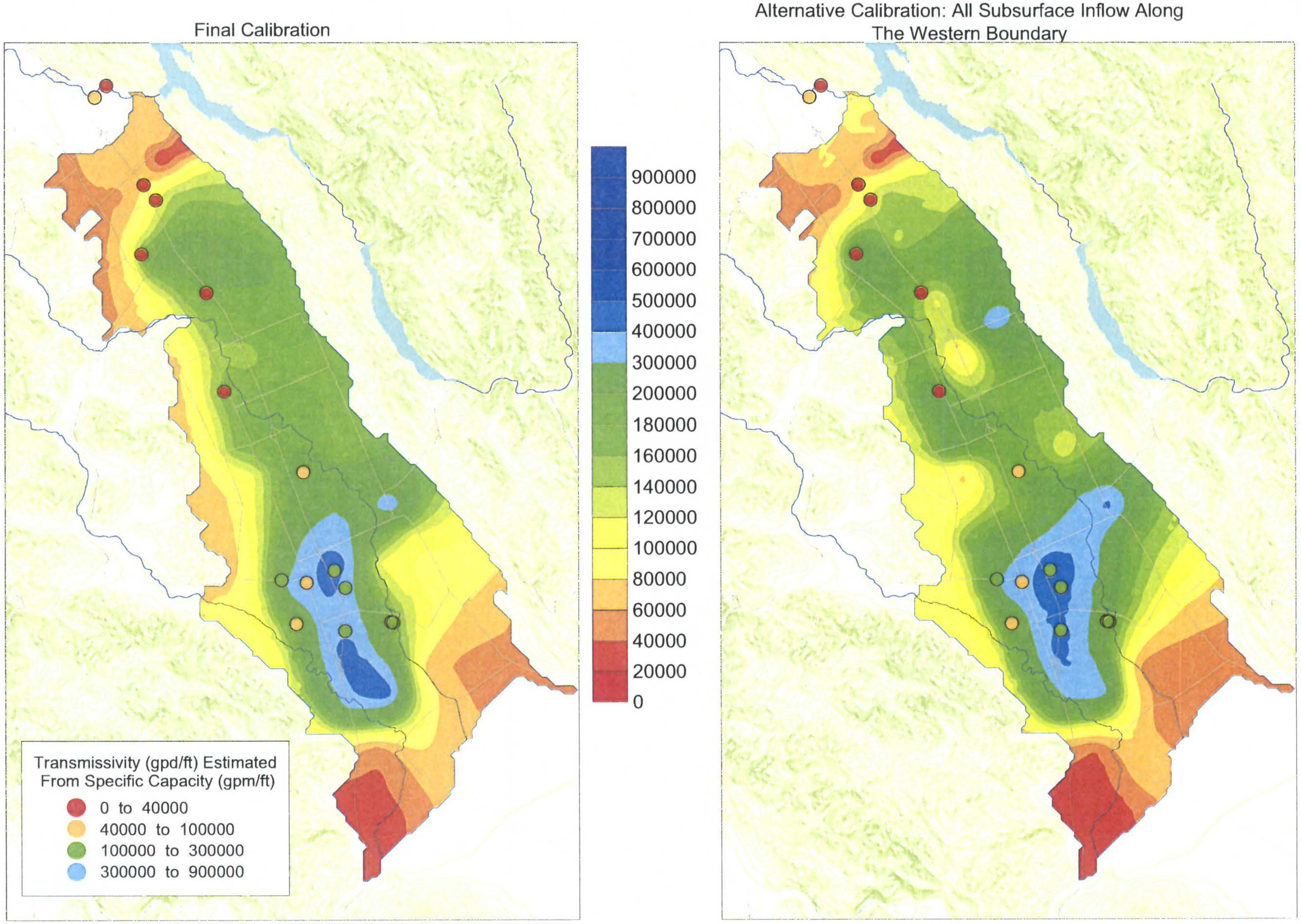


FIGURE ES-8
TRANSMISSIVITY DISTRIBUTION (gpd/ft)
FINAL AND ALTERNATIVE CALIBRATIONS (SCENARIO 1)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 3-15__5/24/05_ccc_sfo

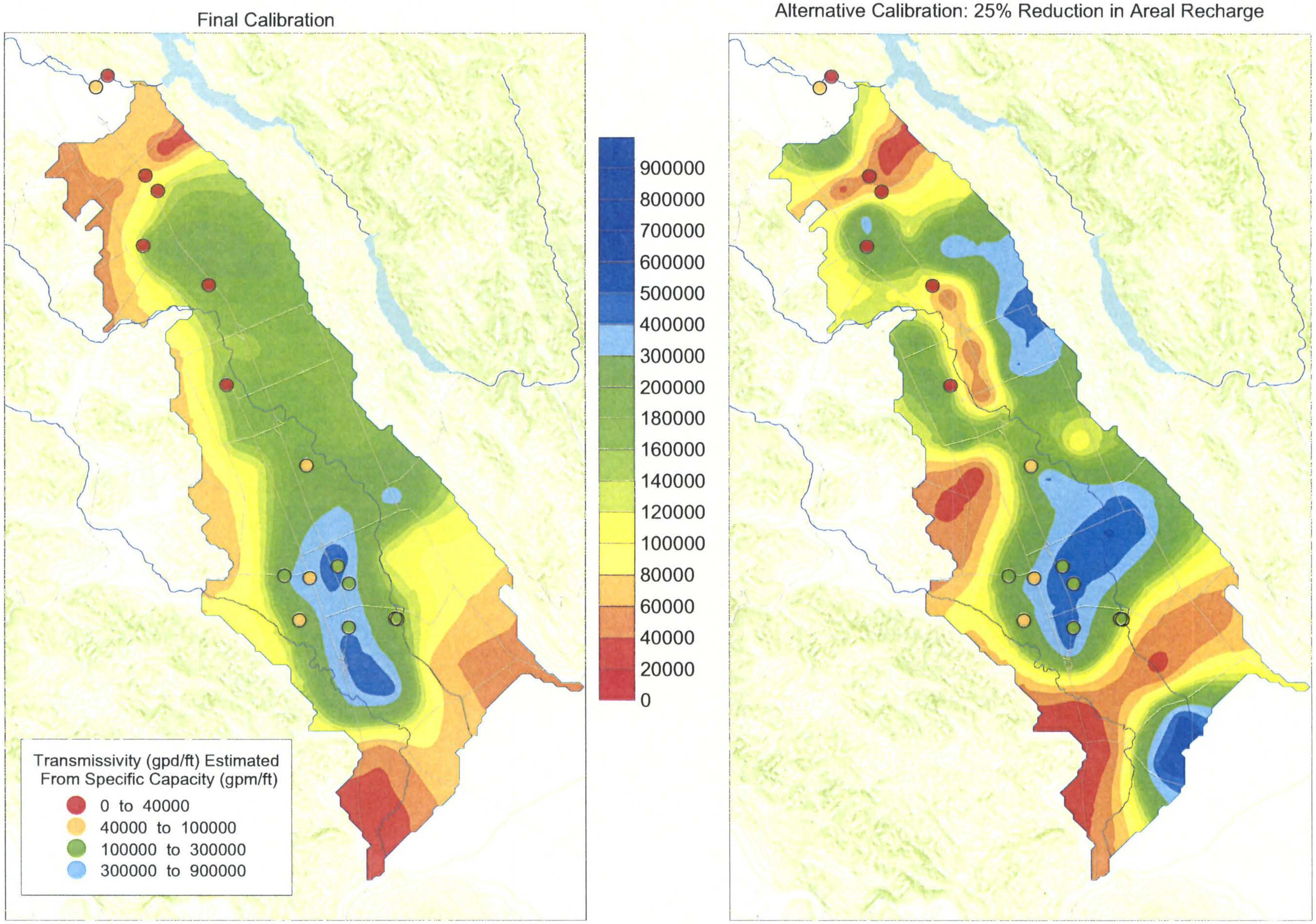


FIGURE ES-9
TRANSMISSIVITY DISTRIBUTION (gpd/ft)
FINAL AND ALTERNATIVE CALIBRATIONS (SCENARIO 2)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 3-19__5/24/05_ccc_sfo

SECTION 1

1.0 Conceptual Model

1.1 Introduction

The Santa Clara Valley Water District (District) recently developed a draft conceptual hydrogeologic model of the Llagas Basin (Abuye, 2003). CH2M HILL conducted a review of the draft conceptual model, existing District databases, and other groundwater-related information to assess how to proceed with development of a numerical model. Where appropriate, the draft conceptual model was refined to facilitate development of the numerical model. Review of the draft conceptual model concentrated on hydraulic layering of the groundwater system through cross sectional analysis, evaluating water level data to identify appropriate steady-state and transient calibration periods, evaluating hydrogeologic properties, and developing a detailed water budget. This section presents results of the draft conceptual model review and refinement.

The Llagas Basin has been previously studied in order to evaluate the hydrogeologic condition of the basin and assess water quality issues specifically related to perchlorate and nitrate contamination. A complete listing of sources referred to in the preparation of this report is presented in Section 4.0, References. The majority of our review focused on the draft conceptual model prepared by the District (Abuye 2003). Other studies primarily focused on regional and local hydrogeology and water quality issues.

1.2 Basin Description

This section describes the location, setting, physiography, climate, and land use of the Llagas Basin.

1.2.1 Physiography

The Llagas Basin is one of three interconnected groundwater basins located in south Santa Clara County (Figure 1-1). The basin is a northwest-southeast trending alluvial valley that extends from the boundary with Coyote Basin (a tributary basin to Santa Clara Valley) about 14 miles southeast to the Pajaro River and the boundary with San Benito County. A well-documented groundwater divide and topographic high separates the Coyote Basin from the Llagas Basin (CH2M HILL 2000; Abuye 2003). The basin is bounded to the east by the Diablo mountain range and extends west about 6 miles at the widest point to the Santa Cruz Mountains. The study area includes the communities of Morgan Hill, San Martin, and City of Gilroy, and covers an area of about 67 square miles (Figure 1-1). Llagas Basin consists primarily of flat alluviated lowlands. Topography generally slopes south toward the Pajaro River, ranging in elevation from about 400 feet above mean sea level (msl) in the north near the boundary with the Coyote Basin to 140 feet msl to the south where the basin meets the Pajaro River (Figure 1-2).

1.2.2 Climate

The area has a Mediterranean-type climate, with warm dry summers and mild winters. Long-term precipitation data for the Llagas Basin were available from the National Oceanic and Atmospheric Administration (NOAA). Monthly precipitation data were obtained for Morgan Hill (Station #45853) for the period 1948 to 2003 and daily precipitation data were obtained for Gilroy (Station #43417) for the period 1957 to 2003. Locations of these stations and others outside the basin boundary are presented on Figure 1-3. For the purposes of this study, precipitation in the basin was estimated using the average from these two stations. Figure 1-4 provides a graphical summary of annual precipitation in Llagas Basin. Historically, precipitation has ranged from 9.2 inches (low – 1985) to 39.7 inches (high – 1983). Figure 1-4 also provides a plot of cumulative departure from mean annual precipitation for the same period and illustrates longer-term climate trends. Drier or drought conditions occurred for the periods 1973 through 1977 and 1983 through 1992, and wetter-than-average conditions occurred during the periods 1977 through 1983 and 1992 through 1998. Average annual rainfall in the Llagas Basin from 1959 to 2002 is 20.3 inches, most of which occurs between the months of November and April. Average precipitation in the uplands and adjacent watersheds is more than double the basin average in some areas. An isohyetal map showing the mean annual distribution of rainfall in the study area is presented in Figure 1-5.

1.2.3 Land Use

Available land use maps for the basin include a 1998 map provided by the District in electronic Geographical Information System (GIS) format and a set of 1990 Department of Water Resource (DWR) land use quad maps. Paper land use maps from DWR (DWR, 1990) were digitized to a geo-referenced map. Land use data presented on the 1990 DWR map were categorized in far greater detail than on the 1998 map. Development of a detailed water budget requires comparisons between the years with available land use data. Therefore, land use data for 1990 and 1998 were merged into five categories that have similar characteristics: (1) wine grapes, deciduous, citrus and subtropical; (2) truck crops and field crops; (3) alfalfa, pasture and turf; (4) barren lands; and (5) native vegetation. Maps of land use in 1990 and 1998 are presented in Figures 1-6A, 1-6B and 1-7. Land use in both years was dominated by truck and field crops and urban landscape. The most significant change in land use from 1988 to 2002 (the proposed period of model calibration) was urban development, which increased to 18,500 acres from about 11,000 acres. The increase in urban development was primarily balanced by a marked decrease in native vegetation, alfalfa, pasture, and turf. Native vegetation decreased to 3,500 acres in 1998 from about 11,000 acres in 1990. Alfalfa, pasture, and turf decreased to 186 acres from 677 acres. Irrigated lands for wine grapes, deciduous, citrus, and subtropical increased to 5,000 acres in 1998 from approximately 3,000 acres in 1990.

1.3 Hydrogeology

This section presents a description of the hydrogeology of the Llagas Basin. The description is based largely on a compilation of information from sources listed in Section 4.0, References. In addition, a project GIS database was developed as part of this study that compiled electronic water level, water quality, lithologic, and pumping information from the District and the United States Geological Survey (USGS). The GIS also includes digital information files generated from maps, tables, and figures developed by the District, DWR, and other consultants that have performed work in the study area.

1.3.1 Hydrogeology of the Llagas Basin

A map showing the surficial geology of the Llagas Basin is presented in Figure 1-8. Principal water-bearing sediments in the Llagas Basin consist primarily of Holocene age alluvial fan deposits, young and old alluvium, and stream deposits. The major sources of alluvial sediments are the Coyote Creek, which drains upland areas to the east, and Uvas and Llagas Creeks, which drain the Santa Cruz Mountains in the west. The alluvium is as much as 500 feet thick in the southern portion of the basin, and consists of poorly consolidated to unconsolidated deposits of clay, silt, sand, and gravel. The alluvial sediments in the Llagas Basin are underlain by the Santa Clara Formation of Plio-Pleistocene age. The Santa Clara Formation consists of consolidated silt, clay, and sand with limited gravel zones (DWR 1981) and unconformably overlies the Franciscan Formation. Because the Santa Clara Formation is semi-consolidated and has a higher clay content than the alluvium, hydraulic conductivity values from this formation are "orders of magnitude" lower than the alluvium (McCloskey and Finneman 1996). Production wells screened exclusively in the Santa Clara Formation in the southern portion of the basin yield very little groundwater. It is not possible to make the distinction between the Santa Clara Formation and overlying alluvium in driller's logs.

Previous studies have separated the basin into two distinct subareas: a forebay subarea in the north and a confined zone in the southern portion of the basin (Iwamura and Wilson 1989; Abuye 2003; DWR 1981). The forebay is largely considered unconfined and is where the majority of the recharge to the basin occurs. The District maintains artificial recharge ponds and streambed facilities in this portion of the basin. South of San Martin, local zones of confinement exist as evidenced by wells that at one time flowed at the surface during winter months (DWR 1981). Increased pumping in the subarea have decreased artesian pressures though some wells still flow above ground surface on a seasonal basis south of Gilroy near the Pajaro River. Confined groundwater conditions in these areas may be attributed to extensive deposits of lake-bottom clays associated with the ancestral Lake San Benito (DWR 1981, Hoose 1986).

1.3.2 Hydrostratigraphic Units

Available driller's logs for wells in the study area were compiled and entered in an electronic database. The majority of the logs were obtained from the District. Within Llagas Basin there were 337 wells with geologic information containing a total of 5,190 descriptive entries, of which 1,081 were unique. Each unique entry was reviewed and placed into one of the 17 Unified Soil Classification System (USCS) categories. These categories were lumped into 7 groups that exhibit similar hydraulic characteristics and were used to construct cross sections. The x-y coordinates for some wells were available from the District or the log itself, and the remainder were assigned approximate values based on digital map files. Cross sections were developed using a "CAT-scan" approach whereby section lines are spaced at even intervals (one mile in this case) parallel and perpendicular to the axis of the basin (Figure 1-9). Using this approach, 22 cross sections were generated that illustrate topography, high and low water levels, bedrock, lithology, and well construction (Figures

1-10 through 1-31). Correlating lithologic groups that exhibit similar hydraulic characteristics in cross sections was not possible.

A bedrock elevation map was developed using cross sections and driller's logs (Figures 1-32 and 1-10 through 1-31). Bedrock structure in the basin resembles a northwest-southeast trending trough. The axis of the trough begins near the boundary with Coyote Basin at an elevation of about -25 feet msl and dips southeast to the Pajaro River where it reaches a minimum elevation of about -500 feet msl. Along the western basin boundary, bedrock elevation begins at about 150 feet msl and gently slopes toward the center of the basin to a minimum elevation of -500 feet msl. Bedrock contact with the eastern boundary is more abrupt, ranging in elevation from 200 feet msl in the northern subarea to -250 feet msl in the southern subarea. The abrupt nature of the eastern boundary is evidenced in numerous well logs (see Figures 1-10 through 1-31) and may be related to the Calaveras Fault. Deep well data south of Gilroy were limited, so bedrock elevation was estimated by spatially interpolating elevations where cross section lines intersect. Elevations were adjusted where necessary to agree reasonably with available observed data. Saturated thickness of the basin was evaluated for steady-state (1996-98) and low (1989-90) water level periods (Figures 1-33 and 1-34). Where saturated thickness was unreasonably thin, bedrock elevation was adjusted accordingly.

As evidenced by cross sections presented in this report and those developed by DWR (1981), alluvial sediments in Llagas Basin lack significant large-scale hydrostratigraphic continuity. Previous reports, discussions with District staff, and water level data suggest the presence of a confined zone from the middle of the basin south to the Pajaro River. However, there is not a specific correlable clay unit related to this confining zone; rather it appears that there is a predominance of clay in this area that, overall, leads to confined behavior (DWR 1981; Hoose 1986). In fact, significant lateral flow still appears possible in this area through relatively thin sand and gravel units.

In the absence of basin-wide hydrostratigraphic layering, the model will consist of four parallel layers that roughly coincide with the distribution of production-well perforations. A clay layer is not explicitly represented in the model. Confined conditions are instead simulated using strong anisotropy (K_h:K_z) ratios. Layering of the model is discussed in more detail in Chapter 2: Numerical Model Development.

1.3.3 Hydrogeologic Properties and Well Yield

Aquifer test data for the study area are limited. Therefore, the majority of the transmissivity values reported herein were estimated using specific capacity data. For wells where only specific capacity data are available the method presented in Driscoll (1995, page 1021) for confined aquifers was used to estimate transmissivity. Hydraulic conductivity estimates were calculated by dividing transmissivity by total screen length of the tested well. Available specific capacity, hydraulic conductivity, and transmissivity data are presented in Figures 1-35 and 1-36 and summarized in Table 1-1. Values of transmissivity range from about 4,000 to about 280,000 gpd/ft, which is equivalent to hydraulic conductivities of 2 to 200 ft/d calculated using the process described above. The highest values of transmissivity are in the southern portion of the basin in the vicinity of the City of Gilroy. Following is a brief description of available aquifer test data.

TABLE 1-1
Transmissivity Estimated from Specific Capacity Data and Aquifer Tests

DWR ID	Pumping Rate (gpm)	Draw-down (ft)	Specific Capacity (gpm/ft)	Transmis-sivity (gpd/ft)	Screen Length (feet)	Hydraulic Conductivity (ft/d)
09S03E09F002	800	94	9	17,076	130	18
09S03E09M002	1,500	67	22	44,910	130	46
09S03E22E006	500	112	4	8,929	135	9
09S03E22P006	520	52	10	20,000	205	13
09S03E34D006	470	220	2	4,273	230	2
09S03E35P004	120	50	2	4,800	120	5
10S03E14A002	600	140	4	8,571	48	24
10S04E19K006	100	5	20	40,000	120	45
10S04E32N002	1,811	13	139	278,615	190	196
11S04E04P009	1,000			88,000	120	350
11S04E04P010	644			160,000	60	100
11S04E05C002	2,376	29	82	163,862	180	122
11S04E06B001	1,267	29	44	87,379	582	20
11S04E06D001	1,169	19	62	123,053	300	55
11S04E08C002	1,649	14	118	235,571	190	166
11S04E06P001	1,279	39	33	65,590	147	60

Pumping test data are available for two wells owned and operated by Gilroy Foods in the southern portion of the basin. A pumping test of Gilroy Foods Well A (11S/04E-04P10) was conducted in March 1994. The well was pumped at 644 gpm for a period of five hours. Transmissivity estimated from the test is on the order of 160,000 gpd/ft, which correlates to a hydraulic conductivity of about 350 ft/d. Well B (11S/04E/04P09), located about 240 feet west of Well A, was tested for eight hours at a rate of 1,000 gpm in September 1986. Estimated transmissivity is about 88,000 gpd/ft, corresponding to a hydraulic conductivity of about 100 ft/d. Well A is screened from 310 to 370 feet bgs and Well B is screened at various intervals between 220 and 370 feet bgs. Transmissivity estimated from these tests may be too high because leakance from confining layers was not considered in the calculations. In general, wells in the basin are screened across multiple aquifers so estimates of transmissivity represent a composite value of aquifer properties.

Well yields in the basin range from 100 to 2,400 gpm. The lowest yields occur in the north subarea, and the greatest in the south subarea. Higher well yields to the south can likely be attributed to a thickening of alluvial sediments in this direction. The majority of high capacity wells in the southern basin are screened in the upper 500 feet of alluvium as evidenced by aquifer test data and City of Gilroy production well information. Higher well yields and transmissivities observed near the City of Gilroy may be attributed to thicker, coarser grain materials being deposited by Uvas Creek as it exits the adjacent drainage.

1.3.4 Water Levels

As part of this study, historical water level data provided by the District were uploaded into an electronic database. The database holds over 4,000 water level entries for 61 wells from 1935 to 2003. Groundwater elevations stored in the database were used to produce hydrographs (Figures 1-37 through 1-44 and 1-48) and groundwater elevation maps (Figures 1-45 and 1-46).

Hydrographs were compiled and reviewed to identify a period of steady-state water levels. Locations of wells with water level data are presented on in Figure 1-37. Figure 1-38 represents hydrographs for all wells in the basin and Figures 1-39 through 1-43 represent wells grouped by township/range. Long-term (1935-2002) hydrographs were plotted for a few wells to assess evaluate historical groundwater lows and assess the effect of climatic trends on groundwater levels (Figure 1-44). The hydrographs indicate that a period of relatively steady and high water levels existed from 1996 to 1998. Using this time period as a basis, average water levels were calculated and used to create a water level map (Figure 1-45).

Hydrographs were also used to identify a period of low water levels. Hydrographs indicate that water levels from 1989 to 1990 were the lowest for the period 1988 to 2002. Average water levels for 1989-1990 were calculated and used to develop a low water level map (Figure 1-46). A water level difference map between the steady-state (high) and low periods indicate the greatest difference between the two periods occurs in the northeast portion of the basin (Figure 1-47).

Groundwater throughout the area generally flows south from the boundary with Coyote Valley towards the Bolsa Basin and Pajaro River. Water level maps for the steady-state period (1996-1998) indicate an average horizontal gradient of about 0.005 in the northern portion of the basin and 0.002 towards the south in the vicinity of Gilroy. During the low water level period (1989-1990) the average horizontal gradient remains consistent with the steady-state period in the north and decreases in the south to about 0.0008. Flatter gradients observed in the south reflect zones of higher transmissivity in this area as evidenced in cross sections and pumping test data discussed below.

Only five wells with water level data also have available screen elevation data. This makes vertical discretization of water levels and identification of vertical gradients difficult. Wells with screen data are plotted on Figure 1-48.

1.4 Water Budget

A water budget represents an accounting of the sources of recharge to and discharge from a groundwater basin. This accounting is generally conducted for as long a period of time (i.e., "period of record") as practical in order to evaluate variations and to identify those components to which the basin is most sensitive. Water budget data for the Llagas Basin are available from 1988 to 2002. Some data are available via direct measurement (e.g., precipitation via rain gage, or pan evaporation). Other data are more difficult to quantify (e.g., subsurface inflow from bedrock uplands, stream seepage, subsurface discharge), and require estimation via commonly used techniques and professional judgment.

1.4.1 Recharge

Primary sources of recharge to the Llagas Basin include intentional recharge to creeks and ponds, deep percolation of water applied for agricultural irrigation and precipitation, subsurface inflow from bedrock uplands and alluvial tributary canyons, and stream seepage. A lesser source of water to the basin is deep percolation of water applied for landscape irrigation. Each of these sources of recharge to the Llagas Basin are described in greater detail below and summarized in Figure 1-49.

Deep Percolation of Precipitation and Water Applied for Agricultural Irrigation

Deep percolation of precipitation and water applied for agricultural irrigation were estimated on a monthly basis utilizing soil moisture budget modeling. The soil moisture budget model is an accounting program that considers all sources and sinks of water to the soil profile on a monthly basis. This information, when combined with information about local crops, evaporation, soil types and soil runoff characteristics, allows calculation of deep percolation to the groundwater system resulting from precipitation on the land surface and water applied for agricultural irrigation. The soil moisture model is dependent upon time series data such as precipitation data from NOAA and relational data such as historic and current land use practices in the basin. Land use data are often the most difficult to obtain but may be the most crucial since land use heavily influences other hydrologic characteristics that are necessary to perform the soil moisture budget. In order to apply the soil moisture budget model change in land use (acreage and type) over time must be estimated. The most significant change in the Llagas Basin is urban development, which doubled to about 20,000 acres in 2002 from 10,000 acres in 1988 (Figures 1-6A, 1-6B and 1-7); also see Section 1.2.3, Land Use. Other soil moisture model inputs include the following:

- *Precipitation* – Addressed in Section 1.2.2, Climate.
- *Evapotranspiration* - Agricultural land use categories were created according to similarities in crop evapotranspiration (ET). ET rates for each crop category were found in DWR Bulletin 113-3, Vegetative Water Use in California. Rates for the Central Coast/Interior Valleys region were used where possible; if ET rates for a particular crop were not available for this region, the ET rates from the South Coast/Interior Valleys were used.
- *Rooting Depth and Depletion Fraction*- Rooting depth and depletion fraction are crop parameters that influence crop water uptake. The source for these parameters was FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration (Allen et al., 1998). Rooting depth for native vegetation was determined from a literature review of native vegetation rooting depths assuming 60 percent grasses and 40 percent woody vegetation, and was confirmed by Blaney, et al. (1963).
- *Soil Parameters* - An overview of the soils in the Santa Clara Valley in the Soil Survey of Eastern Santa Clara Area, California (USDA, 1974) was used to determine soil types on agricultural land. Fine-textured loams such as clay loams and silty clay loams were

found to be the prominent soils on agricultural lands. Therefore, field capacity and permanent wilting point for fine-textured soils were used in the model.

- *Irrigation Efficiency* - Irrigation efficiency was set to 75 percent for the modeling period. We based this assumption on our study of irrigation efficiencies in the Santa Maria River Basin during the same time period.

Preliminary estimates of deep percolation from precipitation and agricultural irrigation based on the soil moisture budget ranged from 1,628 to 38,827 acre-feet per year (afy) for the Llagas Basin, and averaged 17,358 afy. Based on review of the soil moisture model by District staff (SCVWD, 2004) and other modeling adjustments, these estimates were eventually refined to range from 2,620 to 66,246 afy, and average 11,800 afy.

Intentional Recharge to Creeks and Ponds

The District operates a number of artificial recharge facilities in the northern portion of the Llagas Basin. These facilities include four off-stream percolation ponds (Main Avenue, Madrone Channel, San Pedro, and Church Avenue) and three streambed percolation facilities along the Llagas, Uvas, and Tenant Creeks (Figure 1-50). Controlled recharge to these facilities is a major component of groundwater recharge to the Llagas Basin. Creek and pond recharge data for the period 1988 to 2002 were provided by the District and are summarized in Figures 1-51 and 1-52. Recharge from ponds ranges from 5,793 to 15,311 afy and averages 10,631 afy. Creek recharge ranges from 7,474 to 11,651 afy and averages 9,777 afy. Locations of creek recharge are dominated by the position of spreader dams and areas identified as having favorable streambed recharge capacity. Figures 1-53 and 1-54 provided by the District show the location of spreader dams and stream recharge capacity.

Subsurface Inflow from Bedrock Uplands and Alluvial Tributary Canyons, and Stream Seepage

All precipitation in adjacent watersheds and upland areas that is not consumed by evapotranspiration of native vegetation, or held as residual moisture in the soil profile, is available as recharge to the basin. Available recharge from adjacent watersheds was estimated using the Turner method (Turner 1991). Turner (1991) developed an empirical relationship to calculate available recharge, which defines evapotranspiration consumption and residual moisture requirements as a function of precipitation. Using precipitation distributions in the study area (see Figure 1-5), the Turner equation was applied to adjacent watersheds, and available recharge was calculated on an annual basis. Recharge to the basin occurs as subsurface inflow from fractured bedrock along mountain front areas, subsurface inflow from alluvial tributary canyons (i.e. Uvas and Llagas Creeks), and the remainder enters the basin as surface flows. A portion of the surface flows recharge the basin as stream seepage and the remainder continues to flow as surface streams, eventually discharging to the Pajaro River.

Subsurface Inflow from Bedrock

Estimates of subsurface inflow from fractured bedrock along mountain fronts areas were made on an annual basis for the years 1988 to 2002. Estimates assume the permeability of bedrock is about 0.28 ft/d (10^{-5} centimeters per second), the subsurface gradient resembles stream gradients along mountain front areas, and bedrock elevations illustrated in Figure 1-32 are reasonable. Calculated values initially ranged from 393 to 1,683 afy depending on rainfall. Since a significant time lag exists between rainfall, seepage in the watersheds, and subsequent subsurface flow to the basin, these estimates were later refined to remain constant for each stress period. The estimates are dependent on bedrock permeability, the subsurface gradient, and the cross-sectional area of a particular watershed below the alluvium, and are limited by the available recharge calculated by the Turner method. Using this refined approach, subsurface inflow ranges from 728 to 2,648 afy depending on the watershed, which results in a total of about 12,000 afy. The refined estimate corresponds well to the original estimate provided by Abuye (2003).

Subsurface Inflow from Alluvial Tributary Canyons

Significant alluvial tributary canyons exist where the Llagas and Uvas Creeks enter the Llagas Basin along the western boundary. Subsurface inflow from these alluvial canyons was calculated using estimates of transmissivity, hydraulic gradient, and the cross sectional area of the water-bearing strata along the alluvial canyons. Initial estimates of subsurface inflow from the Llagas and Uvas alluvial canyons average 100 afy and 230 afy, respectively. During model development these fluxes were incorporated as part of the stream seepage.

Stream Seepage

Remaining yield available for recharge enters the basin as surface flows. Estimates of stream seepage were made on an annual basis for the years 1988 to 2002. Estimates assume about 10 percent of surface flows recharge groundwater in the basin and the remainder eventually discharges to the Pajaro River. Initial estimates ranged from 216 to 7,387 afy. The average value for the time period is 2,753 afy. However, similar to subsurface inflow, these estimates were later refined based on calculations made for individual watersheds and the estimate assumed to recharge groundwater was reduced from 10 percent to 5 percent.

Northern Boundary

A groundwater divide separates the Llagas and Coyote Basins, and subsurface inflow is assumed not to occur across this divide. However, the boundary varies based on relative conditions between the two basins. This boundary will serve as a water budget calibration parameter, using groundwater gradient information for the purposes of bracketing a range of reasonable values.

Deep Percolation of Water Applied for Landscape Irrigation

The only other notable source of recharge to the Llagas Basin includes deep percolation of water delivered for domestic use. It was assumed that 50 percent of delivered water (domestic and municipal pumping) is applied for landscape irrigation and five percent of this applied water returns to the groundwater system via percolation. Recharge due to from landscape irrigation practices ranges from 666 to 1,005 afy, averaging 816 afy.

1.4.2 Discharge

Sources of discharge from the Llagas Basin include groundwater pumpage, groundwater consumption by phreatophytes, underflow across the southern boundary to the Bolsa Basin, and discharge to Pajaro River.

Pumping

The primary source of discharge from the Llagas Basin is groundwater pumpage for municipal and industrial (M&I), agricultural, and domestic use. Available pumping well locations, rates, construction details, and lithology for wells in the Llagas Basin were uploaded to the GIS. Initially, screen data were available for about 21 percent of the pumping in the basin. Additional well logs were obtained from the District and uploaded to the database. After this update, wells with screen data account for about 36 percent of the pumping in the basin. Remaining pumping wells were assigned screens using an algorithm that relies on interpolating from wells with known screen intervals. A description of the algorithm is presented in Appendix A.

Pumping rates and locations provided by the District are based on the District groundwater extraction database. The District collects a user fee based on the number of acre-feet pumped during 6-month billing periods (January to June, and July to December). Groundwater extraction fees are imposed on individual industrial, municipal, agricultural, and residential water users. The amount is based on the estimated quantity of groundwater extracted by each user. Estimates are made by a variety of methods including metering, crop demand rates, and electrical charges. Total groundwater extraction during the period 1988 through 2002 ranged from 32,037 to 44,274 afy, averaging 39,388 afy. The majority of groundwater extraction is associated with M&I and agricultural pumpage (Figure 1-55).

Consumption by Phreatophytes

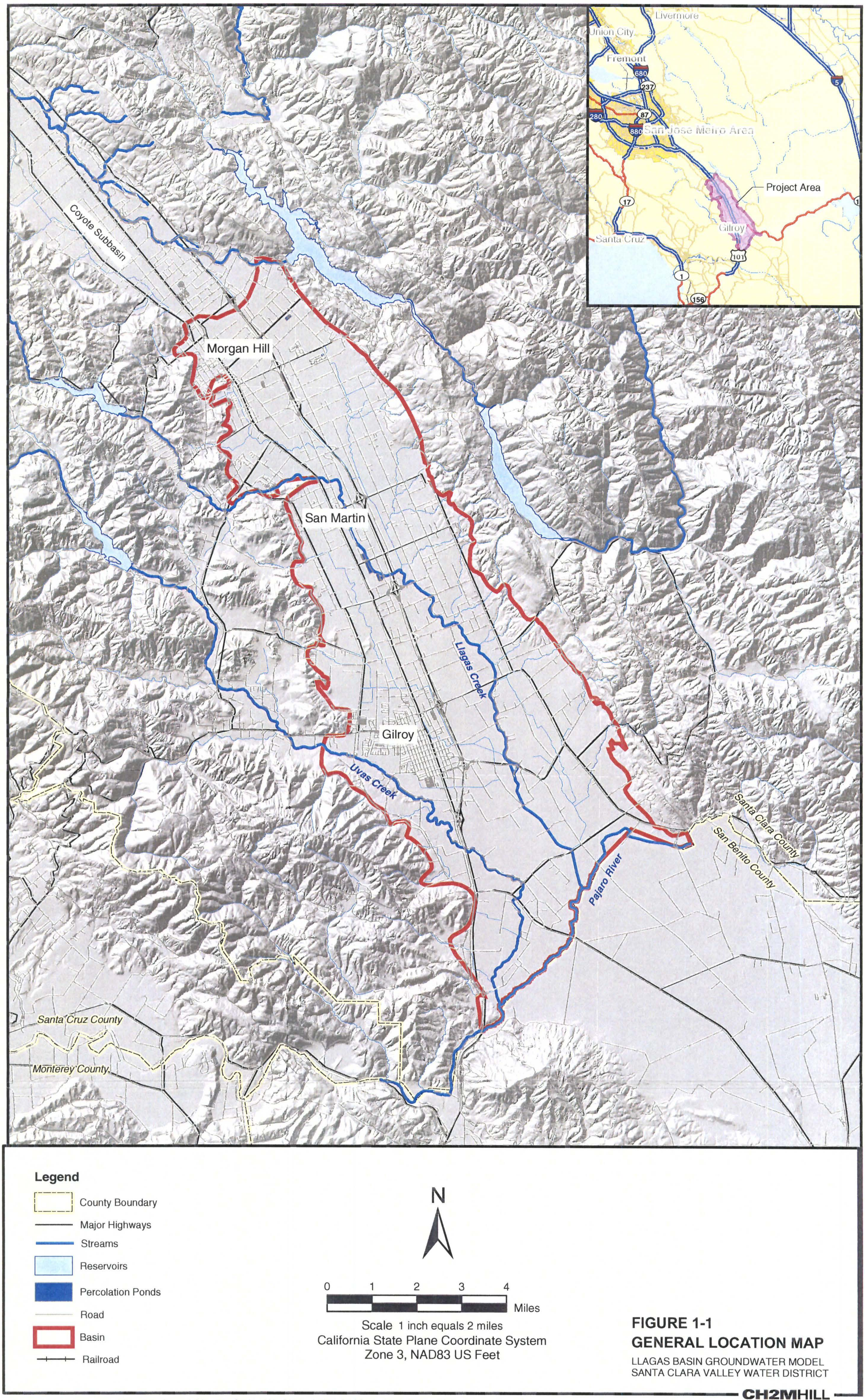
Phreatophytes in both wetland and riparian habitats within the Llagas Basin uptake groundwater directly. Wetlands currently cover about 530 acres in Llagas Basin (Abuye 2003). Since wetland habitats are generally protected it was assumed this acreage did not change from 1988 to 2002. Phreatophytes in Llagas Basin are estimated to consume about 1-2 afy of groundwater in these areas (Abuye 2003). Based on these assumptions, average consumption of groundwater by phreatophytes is estimated to be 795 afy. Consumption by phreatophytes was not explicitly simulated in the model. Instead, discharge to these areas was eventually simulated as part of discharge to drains.

Southern Boundary

The southern boundary with Bolsa Basin is hydraulic in nature, and subject to variation based on conditions outside of and within the basins (i.e., driven by water level variations). Groundwater may flow across this boundary. This parameter will be varied and evaluated during calibration using groundwater gradient information for the purposes of bracketing a range of reasonable values. Estimates of subsurface discharge to the Bolsa Basin range from about 2,200 to 5,500 afy. This range is based on preliminary estimates of transmissivity, hydraulic gradient, and cross sectional area of the water-bearing strata along the boundary of the basin. Applying a similar procedure, Abuye (2003) estimates an average of 1,800 afy discharge to the Bolsa Basin from 1988 to 2002.

Groundwater Discharge to Pajaro River

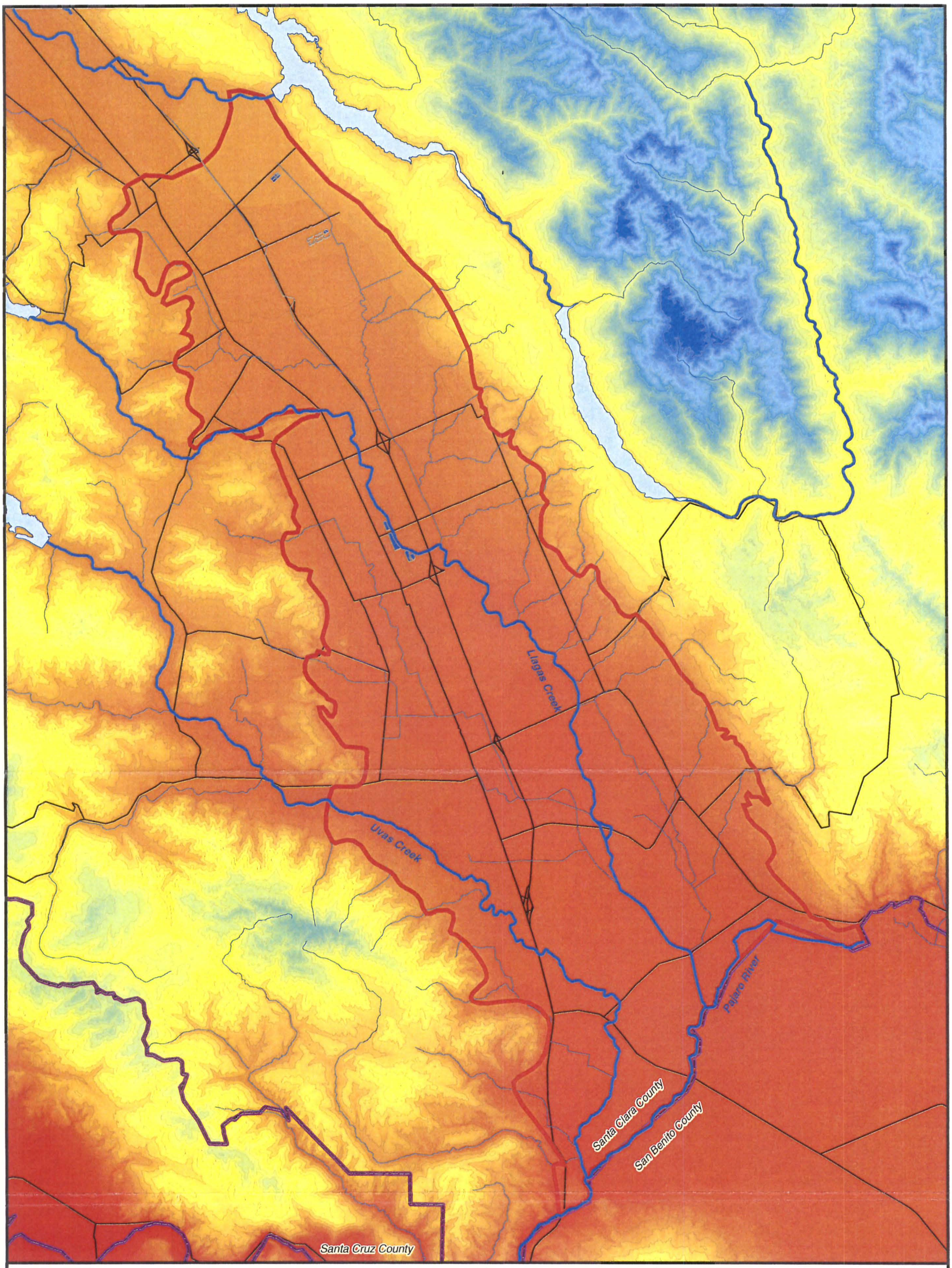
Flowing wells along the Pajaro River indicate that the river serves as a discharge boundary for groundwater in the Llagas Basin. Groundwater discharge to the Pajaro River will be a model computed value and serve as a water budget calibration parameter, using monthly stream flow data from the Chittenden gage (USGS gage 11159000) for the purposes of bracketing a range of reasonable values.



Scale 1 inch equals 2 miles
California State Plane Coordinate System
Zone 3, NAD83 US Feet

FIGURE 1-1
GENERAL LOCATION MAP
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Scale 1 inch equals 8,000 feet
California State Plane Coordinate System
Zone 3, NAD83 US Feet

FIGURE 1-2
TOPOGRAPHY

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

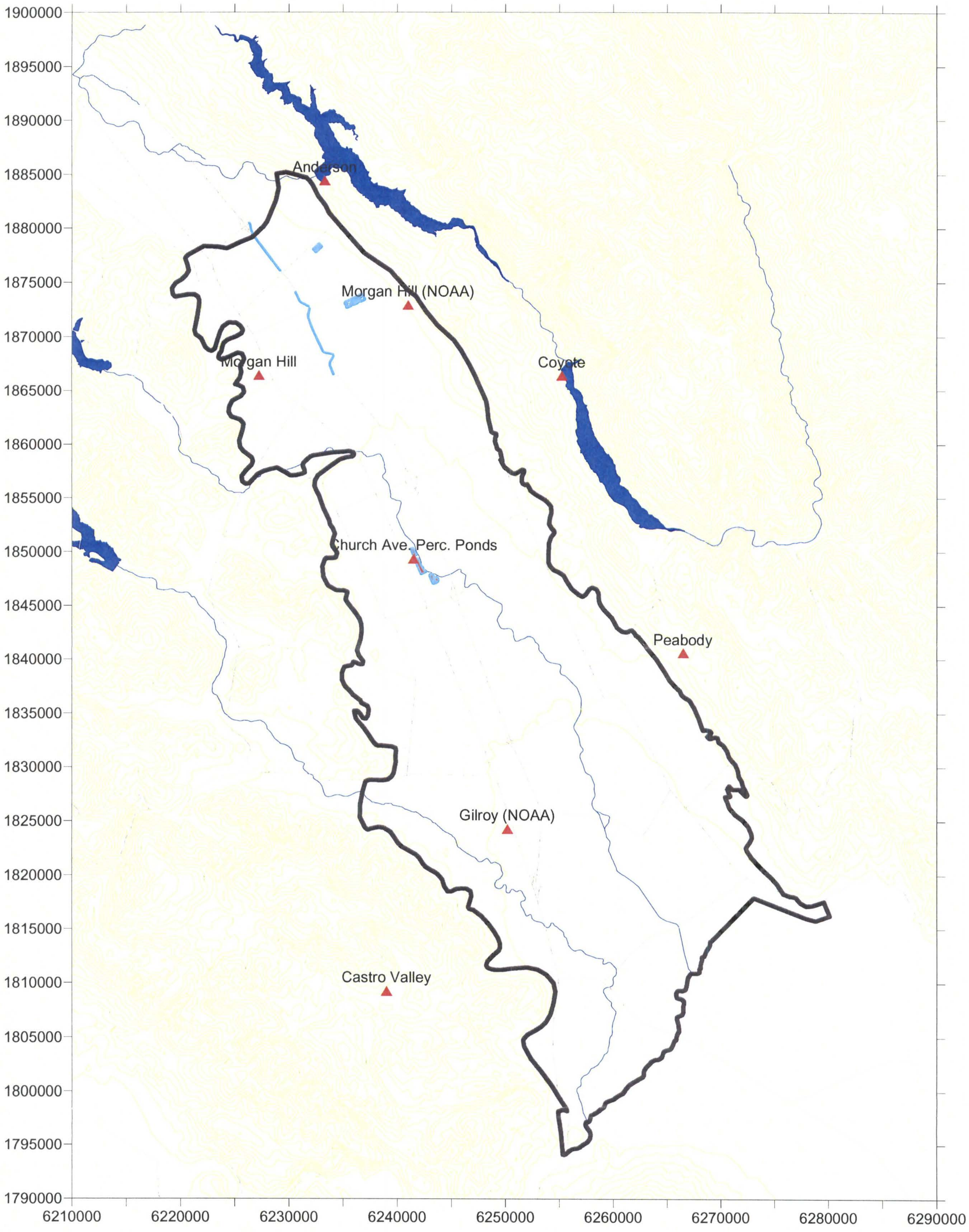


FIGURE 1-3
RAIN GAGE LOCATIONS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 2-3_4/15/04_ccc_sfo

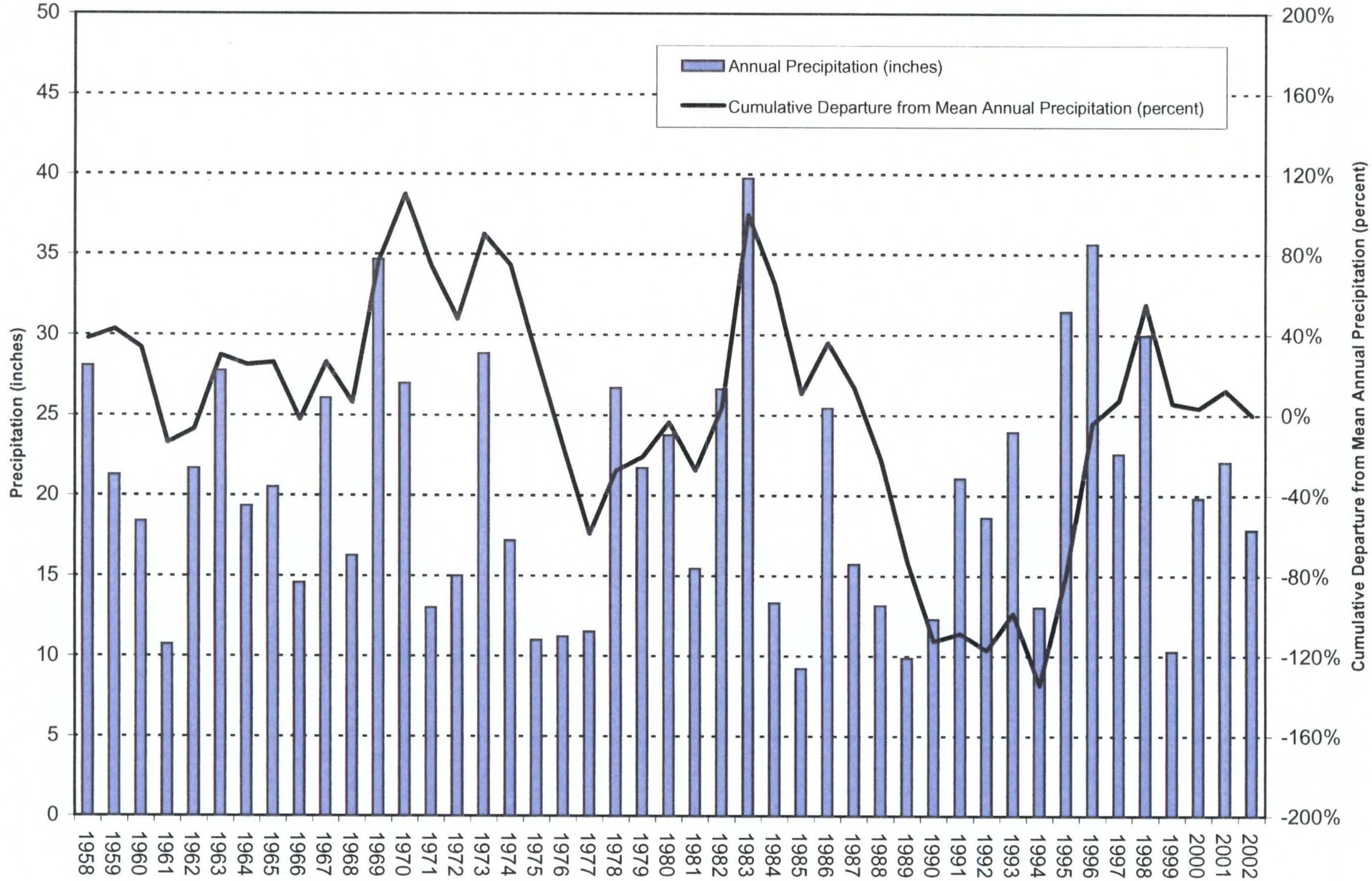
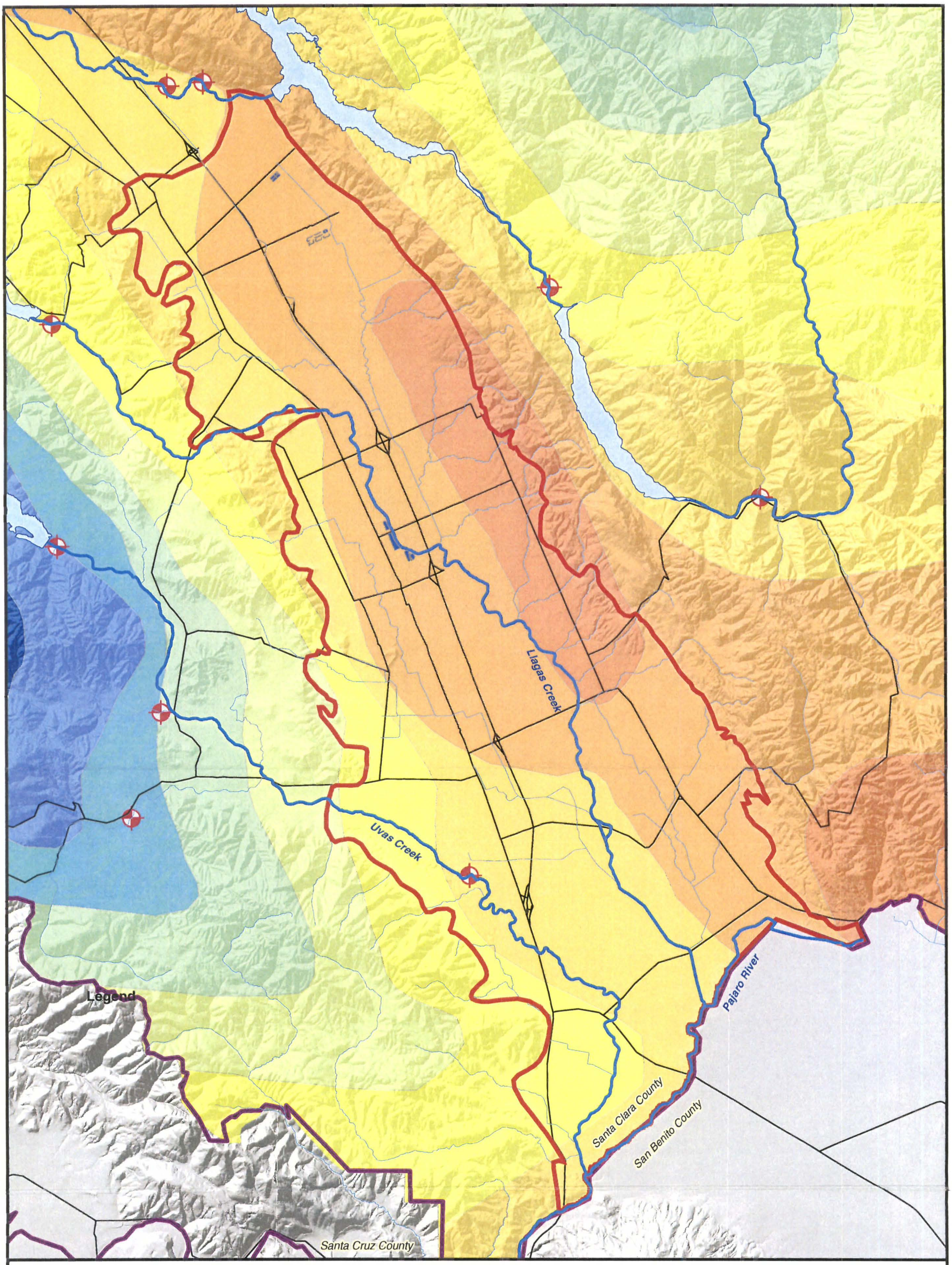


FIGURE 1-4
PRECIPITATION DATA AND CLIMATIC TRENDS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

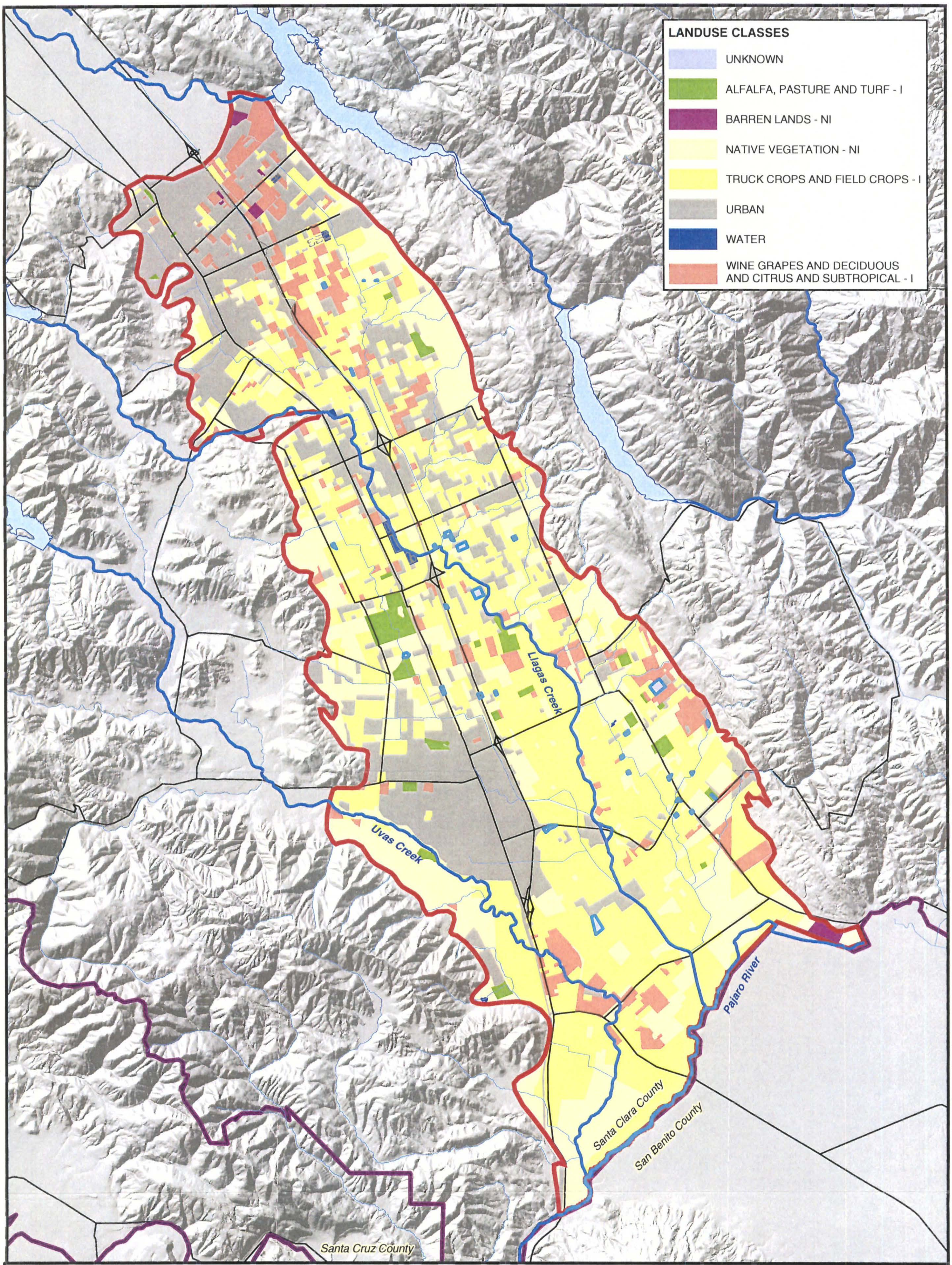
188409.LB.05 _Fig 2-4_4/15/04_ccc_sfo



Scale 1 inch equals 8,000 feet
California State Plane Coordinate System
Zone 3, NAD83 US Feet

FIGURE 1-5
Mean Annual Precipitation for 100 Years of Historical Data
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Legend

- ▭ Basin
- ▭ County Boundary
- ■ Percolation Ponds
- ▭ Reservoirs
- — Major Highways
- ┼┼ Railroad
- — Streams

N

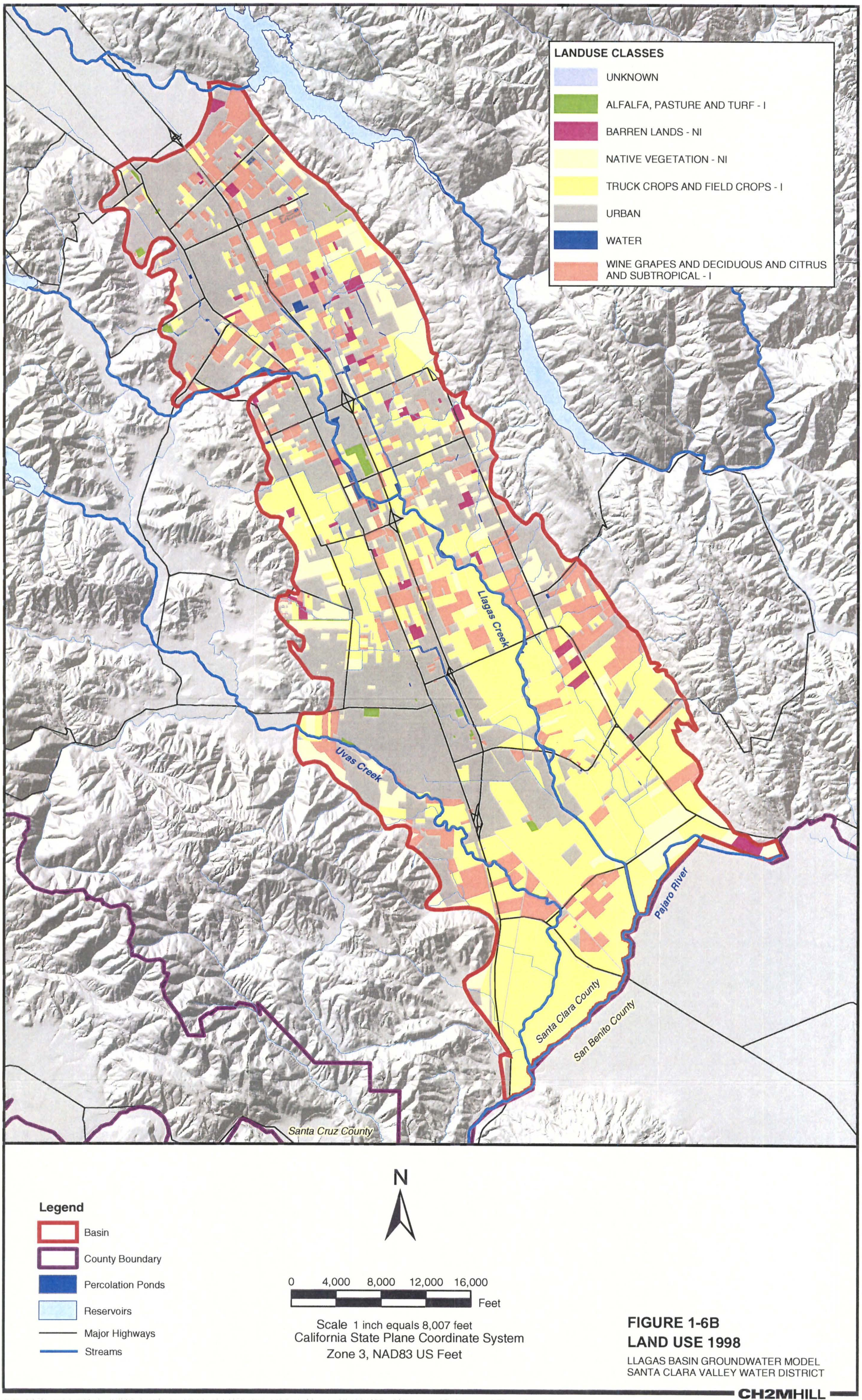
0 4,000 8,000 12,000 16,000 Feet

Scale 1 inch equals 8,000 feet
California State Plane Coordinate System
Zone 3, NAD83 US Feet

FIGURE 1-6A
LAND USE 1990

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Scale 1 inch equals 8,007 feet
California State Plane Coordinate System
Zone 3, NAD83 US Feet

FIGURE 1-6B
LAND USE 1998

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

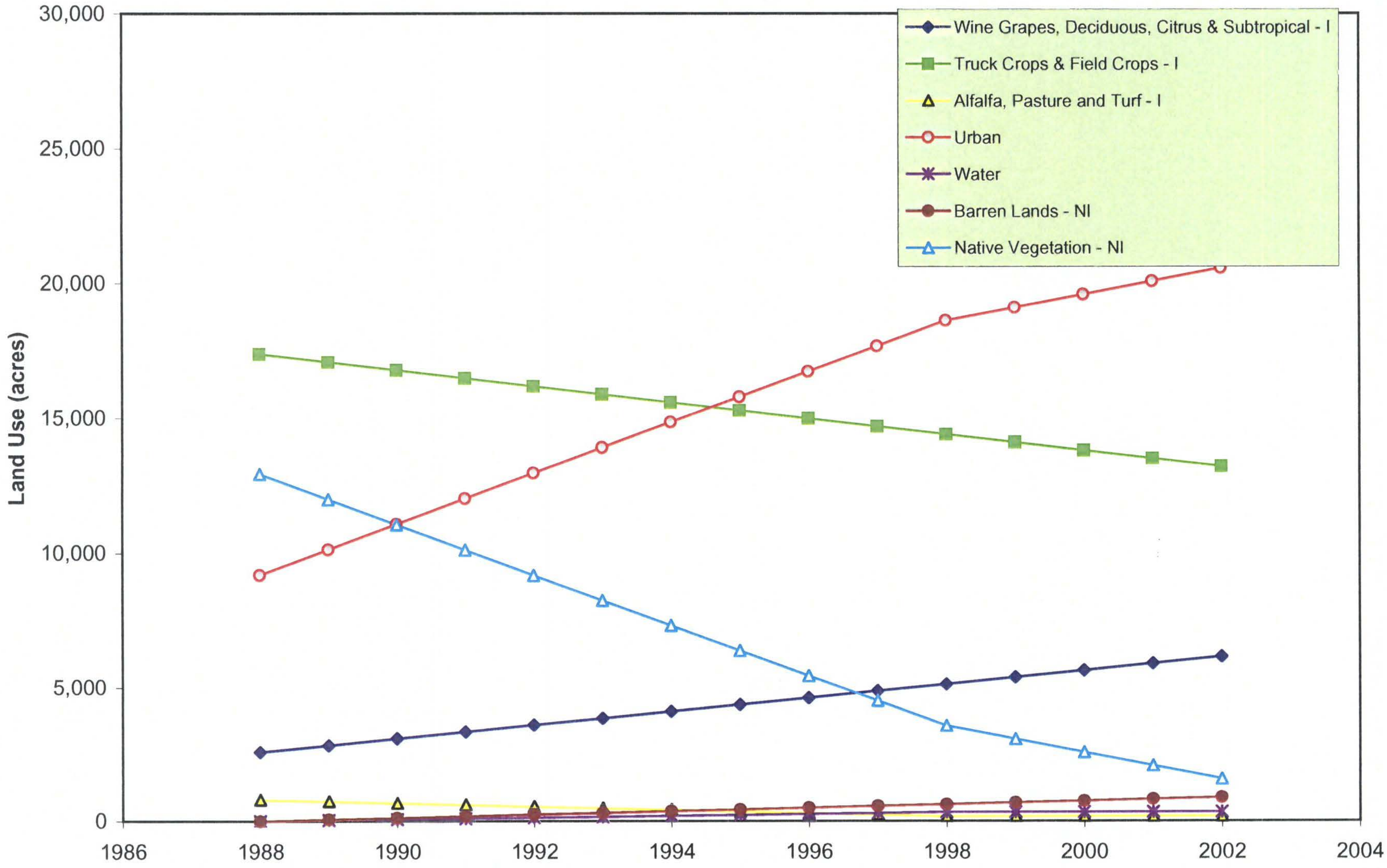


FIGURE 1-7
LAND USE TRENDS

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 2-7_4/15/04_ccc_sfo

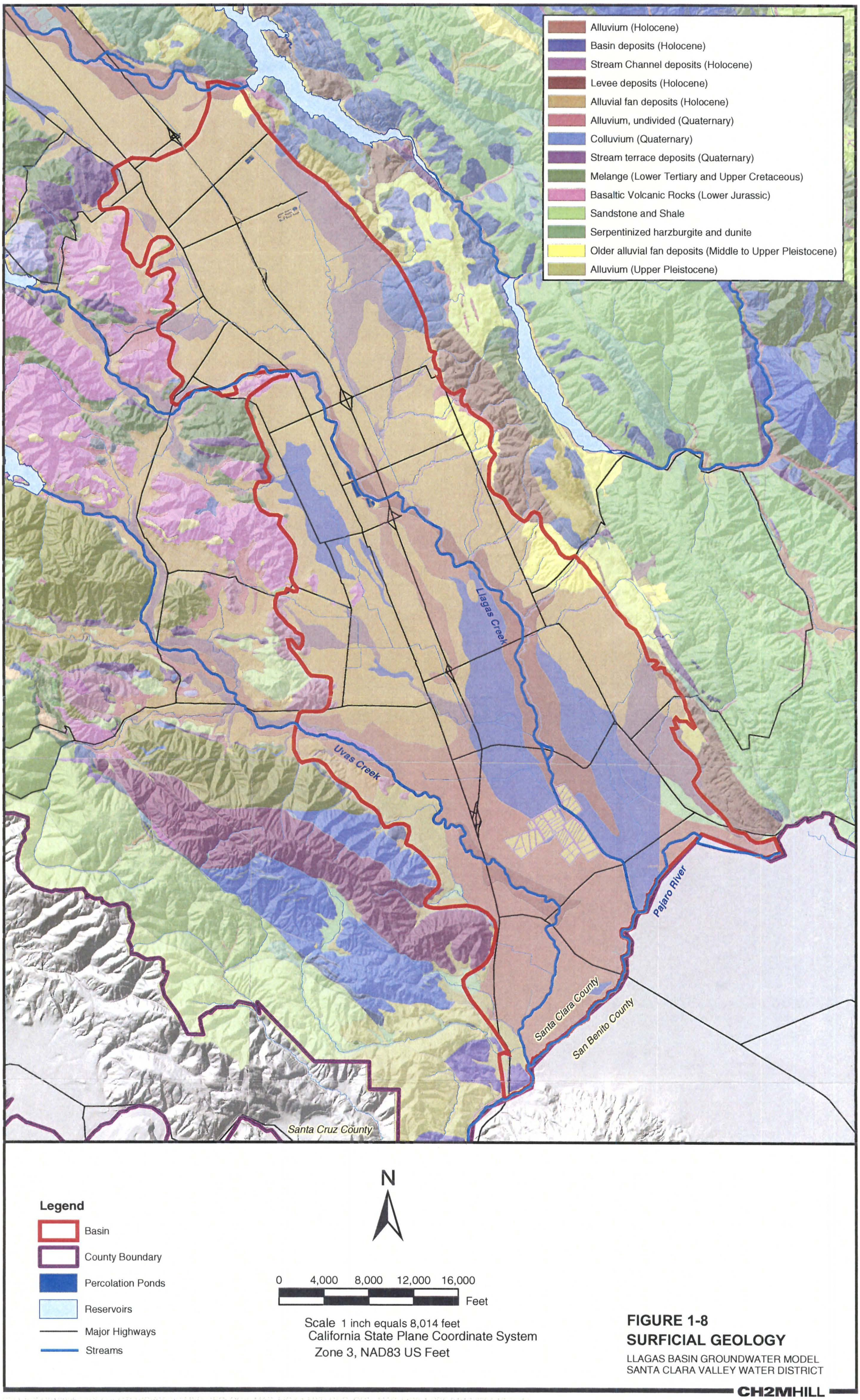

Alluvium (Holocene)
Basin deposits (Holocene)
Stream Channel deposits (Holocene)
Levee deposits (Holocene)
Alluvial fan deposits (Holocene)
Alluvium, undivided (Quaternary)
Colluvium (Quaternary)
Stream terrace deposits (Quaternary)
Melange (Lower Tertiary and Upper Cretaceous)
Basaltic Volcanic Rocks (Lower Jurassic)
Sandstone and Shale
Serpentinized harzburgite and dunite
Older alluvial fan deposits (Middle to Upper Pleistocene)
Alluvium (Upper Pleistocene)
152
Llagas Creek
Uvas Creek
Pajaro River
Santa Clara County
San Benito County
Santa Cruz County
Legend
Basin
County Boundary
Percolation Ponds
Reservoirs
Major Highways
Streams
N
0
4,000
8,000
12,000
16,000
Feet
Scale 1 inch equals 8,014 feet
California State Plane Coordinate System
Zone 3, NAD83 US Feet
CH2MHILL

FIGURE 1-8
SURFICIAL GEOLOGY
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

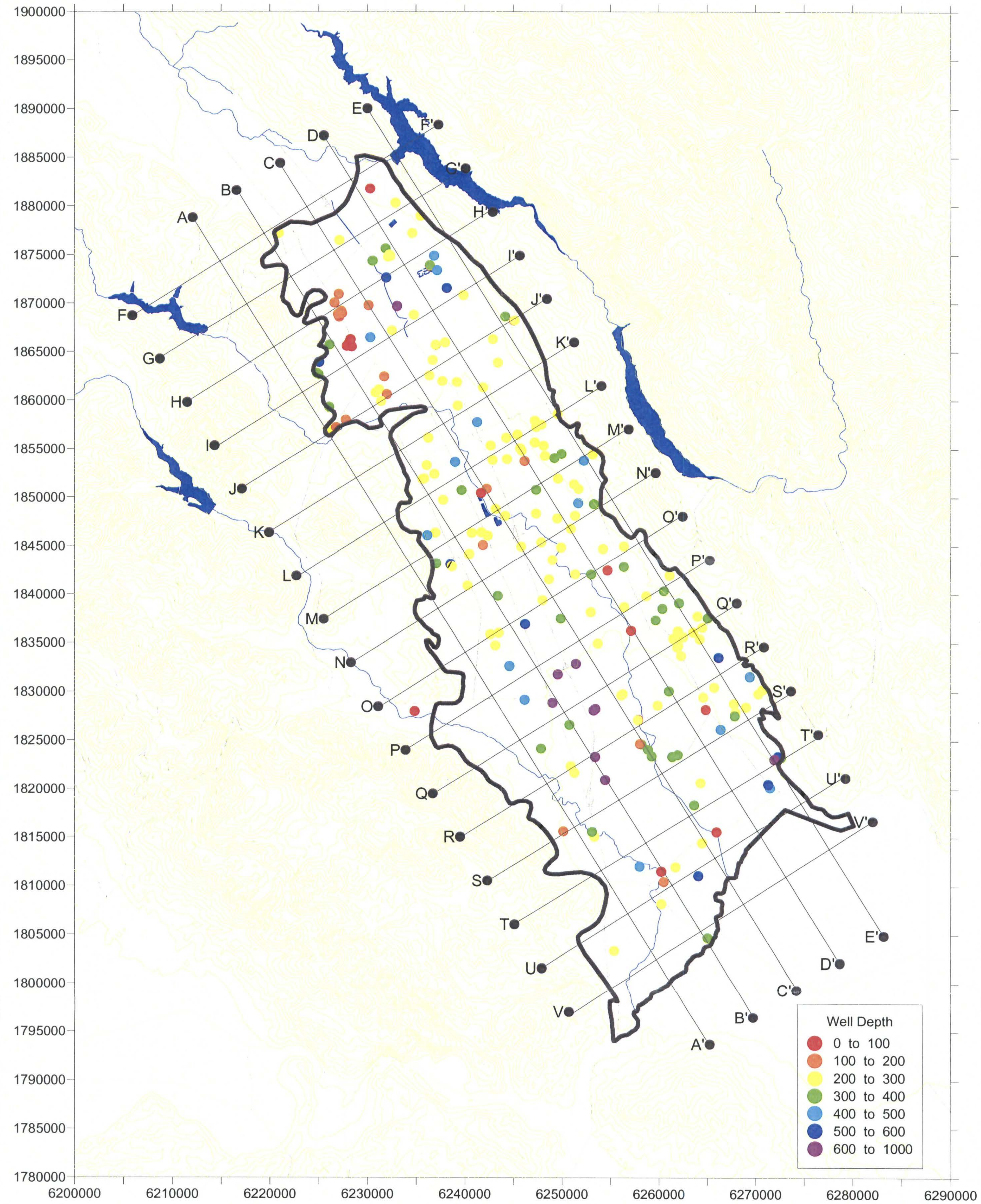
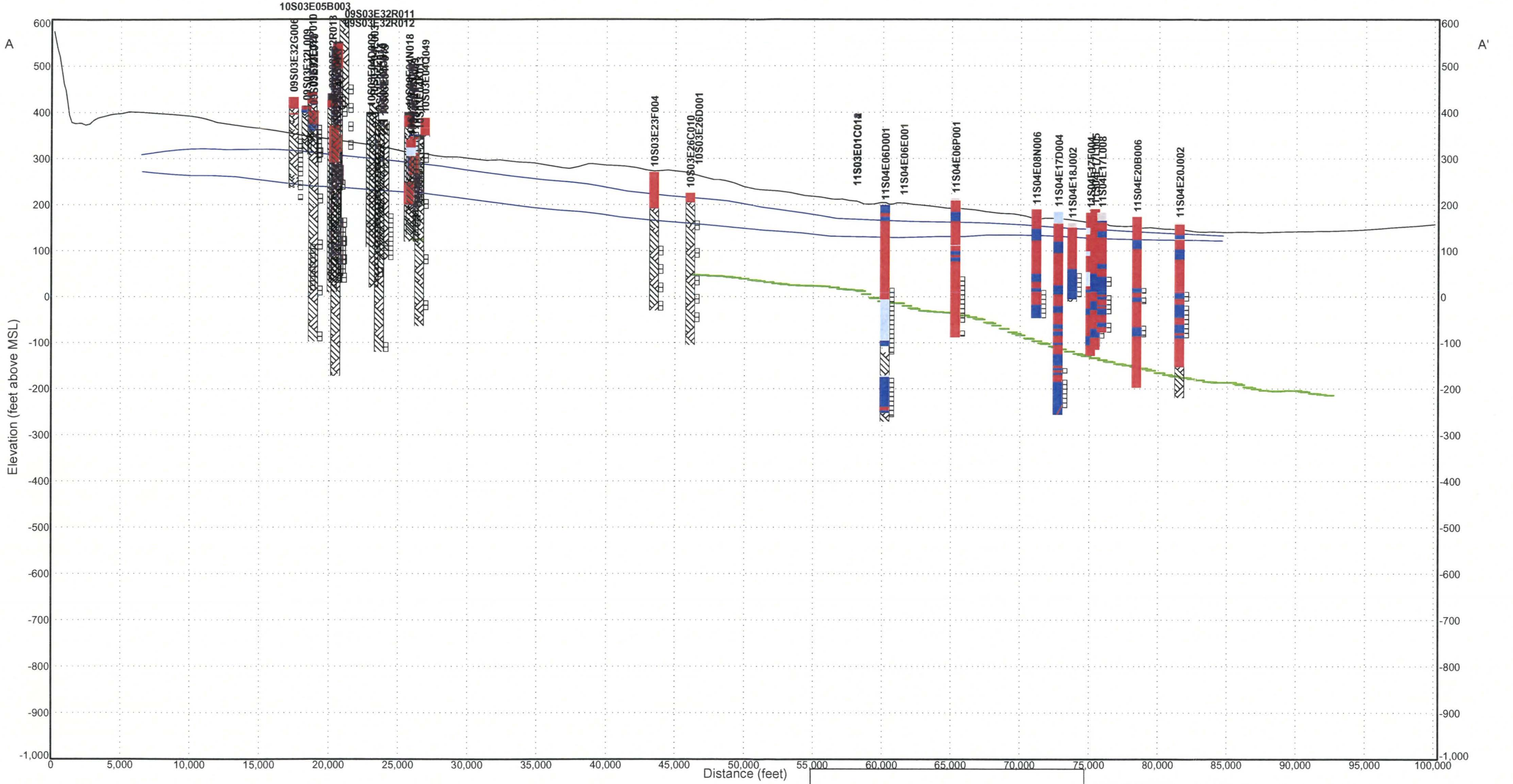


FIGURE 1-9
CROSS SECTION LOCATION MAP
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

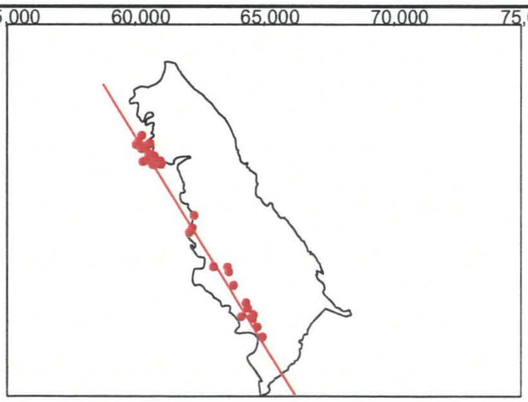
CH2MHILL



Legend

▤ Well Screen

🟦 GP	☐ SP	🟨 ML	▨ BR
🟦 GW	☐ SW	🟨 MH	🟥 CL
▨ GM	▨ SM	☐ FL	🟥 CH
▨ GC	▨ SC	■ PT	■ OH
			■ OL



XSection A-A'

Santa Clara Valley

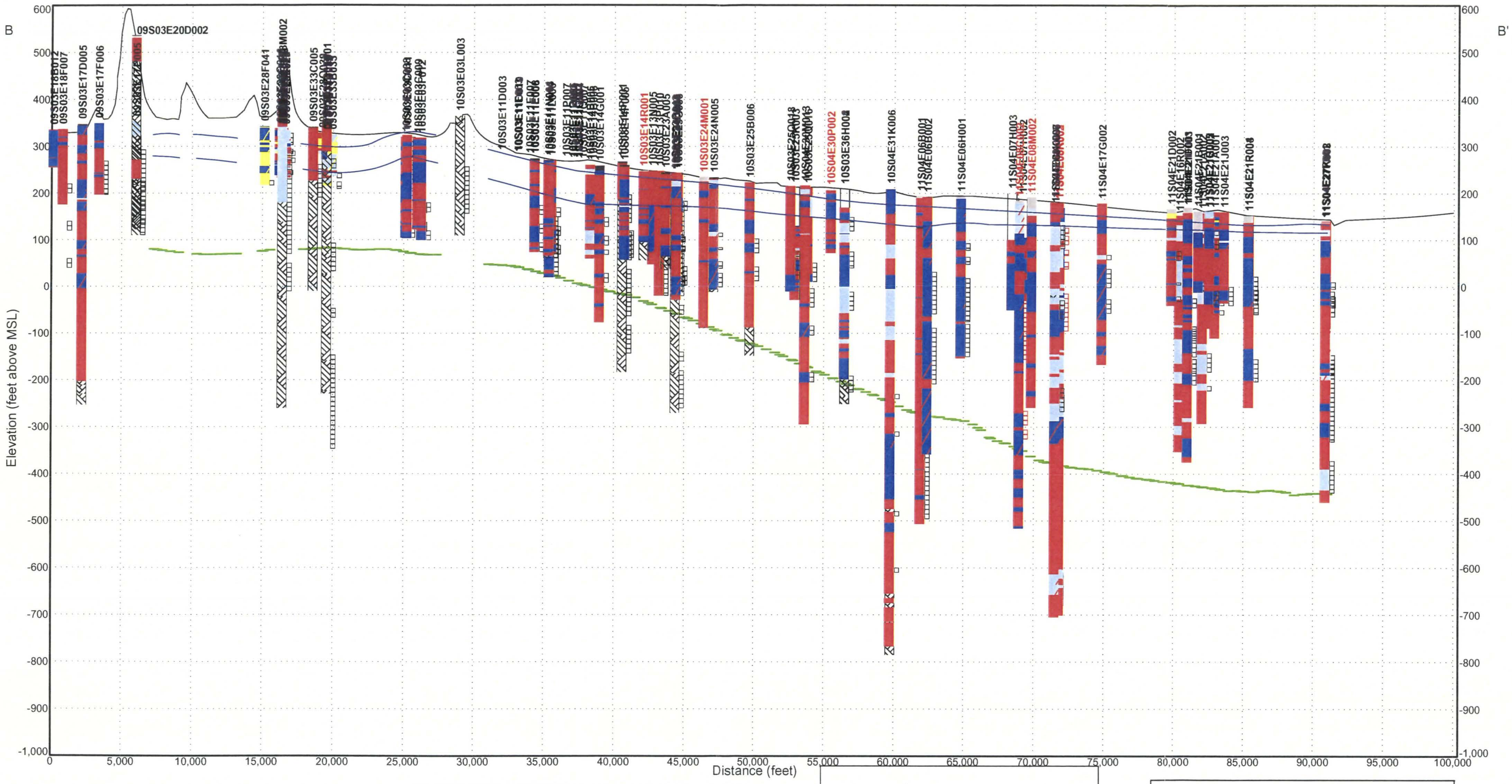
Date: 02 Mar 04 | Figure

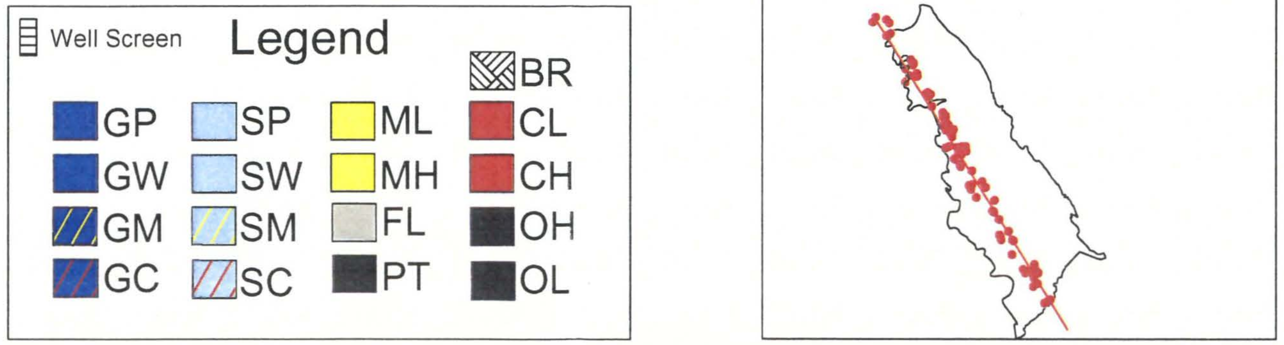
G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/19/2004

FIGURE 1-10
CROSS SECTION A-A'

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

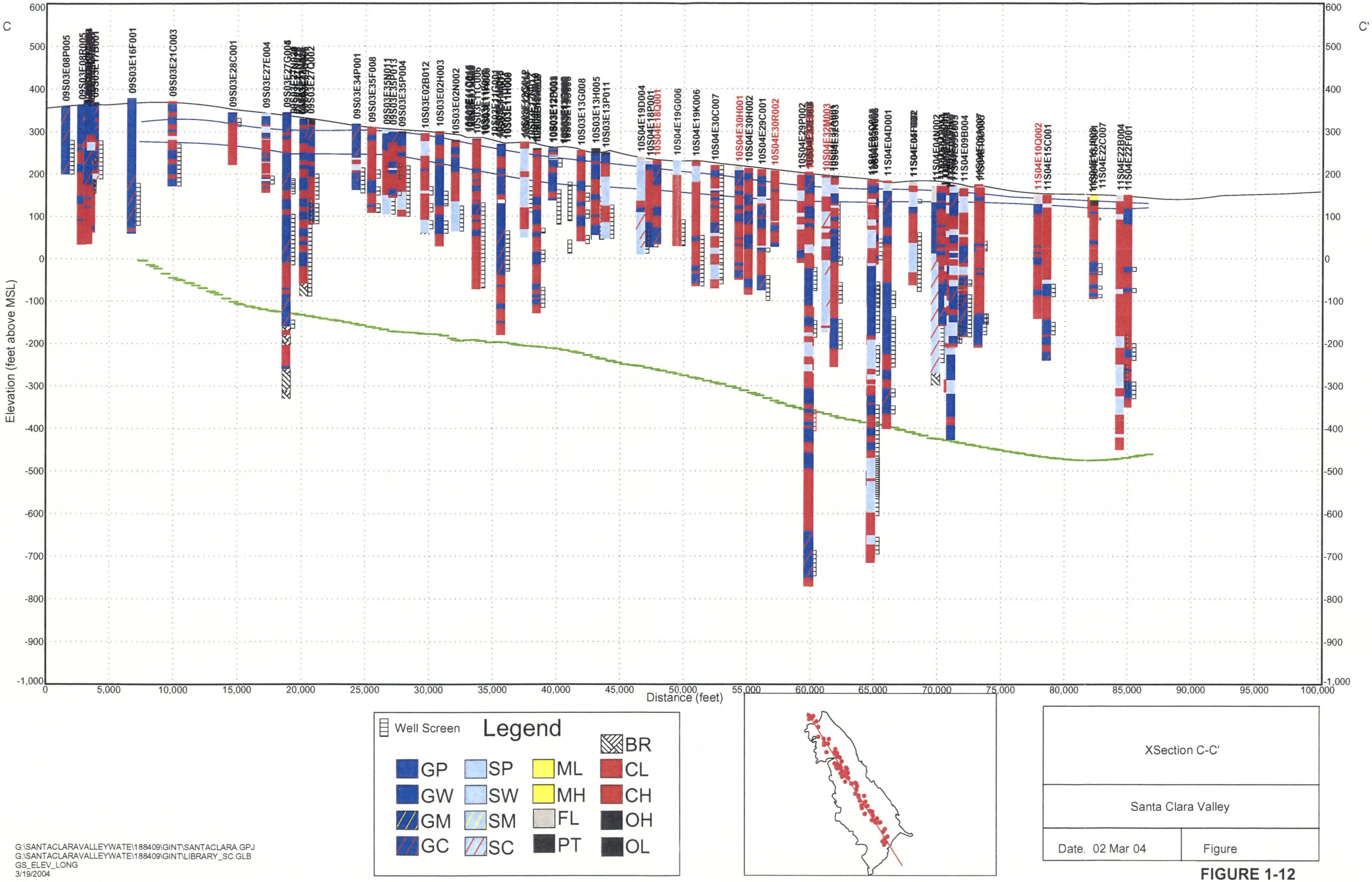




G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/2/2004

XSection B-B'
Santa Clara Valley
Date: 02 Mar 04 | Figure

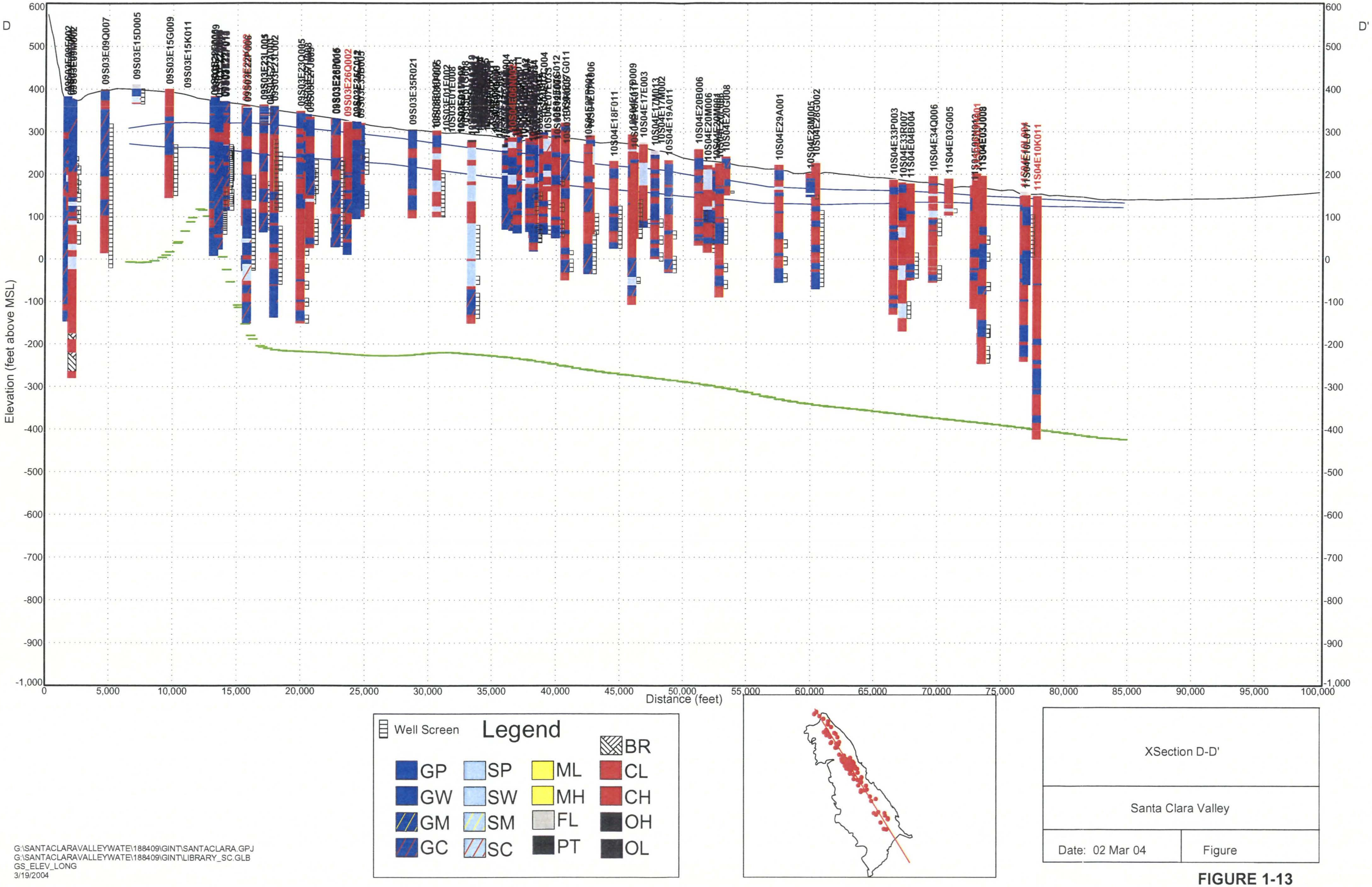
FIGURE 1-11
CROSS SECTION B-B'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL



G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/19/2004

XSection C-C'	
Santa Clara Valley	
Date. 02 Mar 04	Figure

FIGURE 1-12
CROSS SECTION C-C'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL



G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/19/2004

XSection D-D'

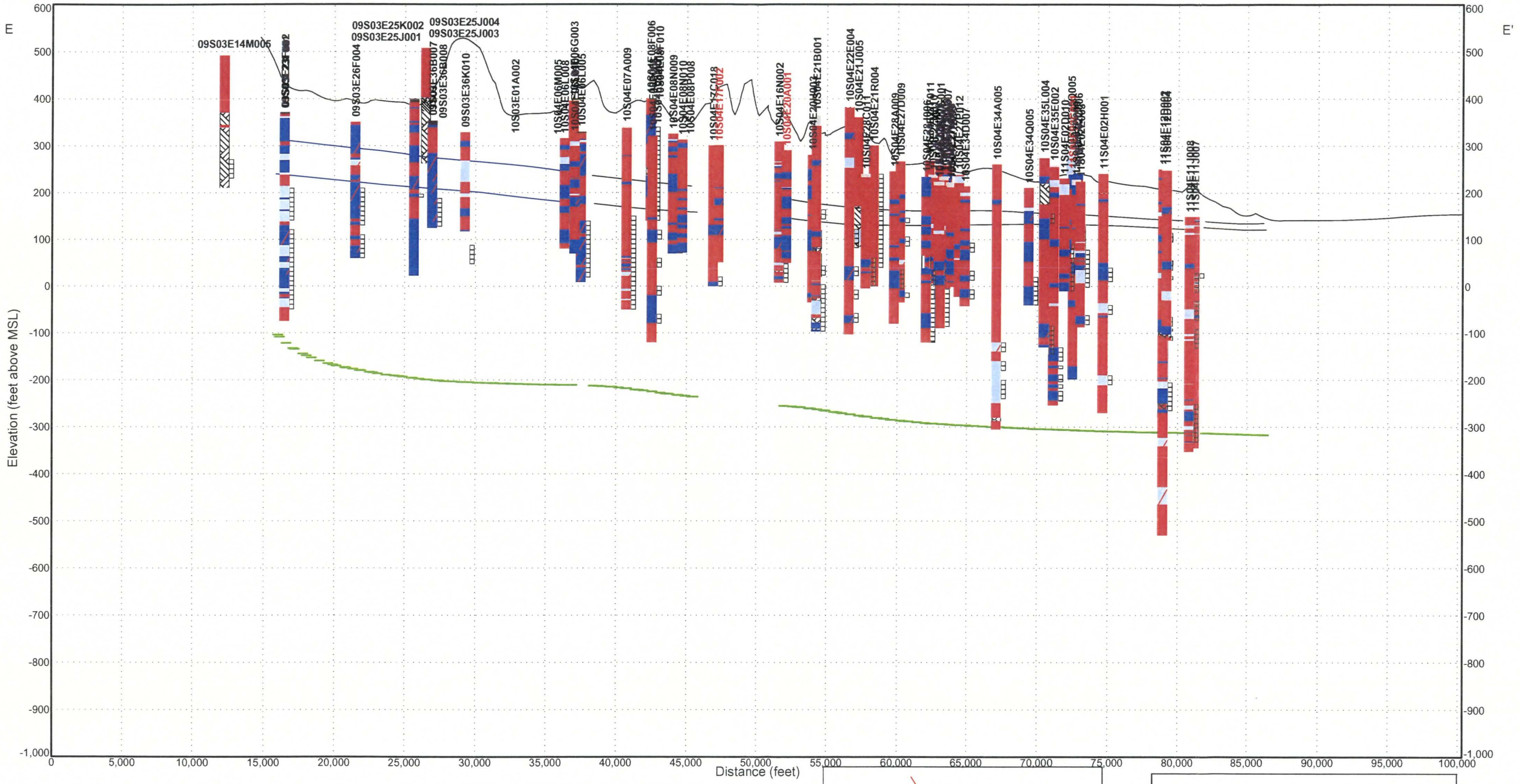
Santa Clara Valley

Date: 02 Mar 04

Figure

FIGURE 1-13
CROSS SECTION D-D'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL

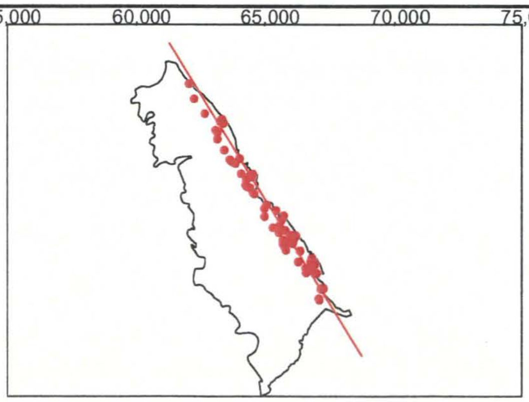
188409.LB.05 _Fig 3-6_4/16/04_ccc_sfo



- ▤ Well Screen

Legend

			▨ BR
🟦 GP	🟦 SP	🟨 ML	🟥 CL
🟦 GW	🟦 SW	🟨 MH	🟥 CH
▨ GM	▨ SM	⬜ FL	⬛ OH
▨ GC	▨ SC	⬛ PT	⬛ OL

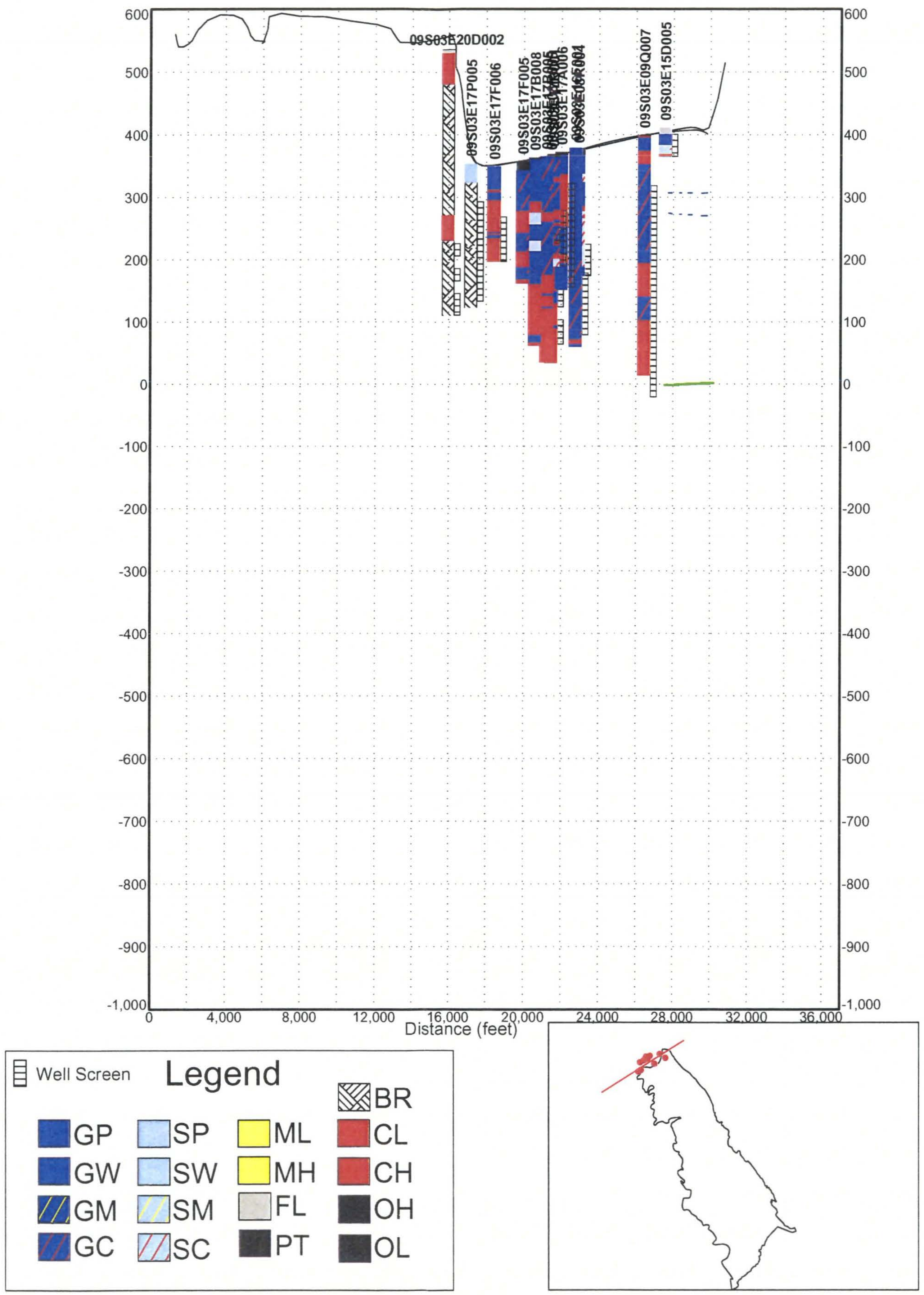


G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/19/2004

XSection E-E'	
Santa Clara Valley	
Date: 02 Mar 04	Figure

FIGURE 1-14
CROSS SECTION E-E'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL

188409 LB 05 _Fig 3-7_4/16/04_ccc_sfo

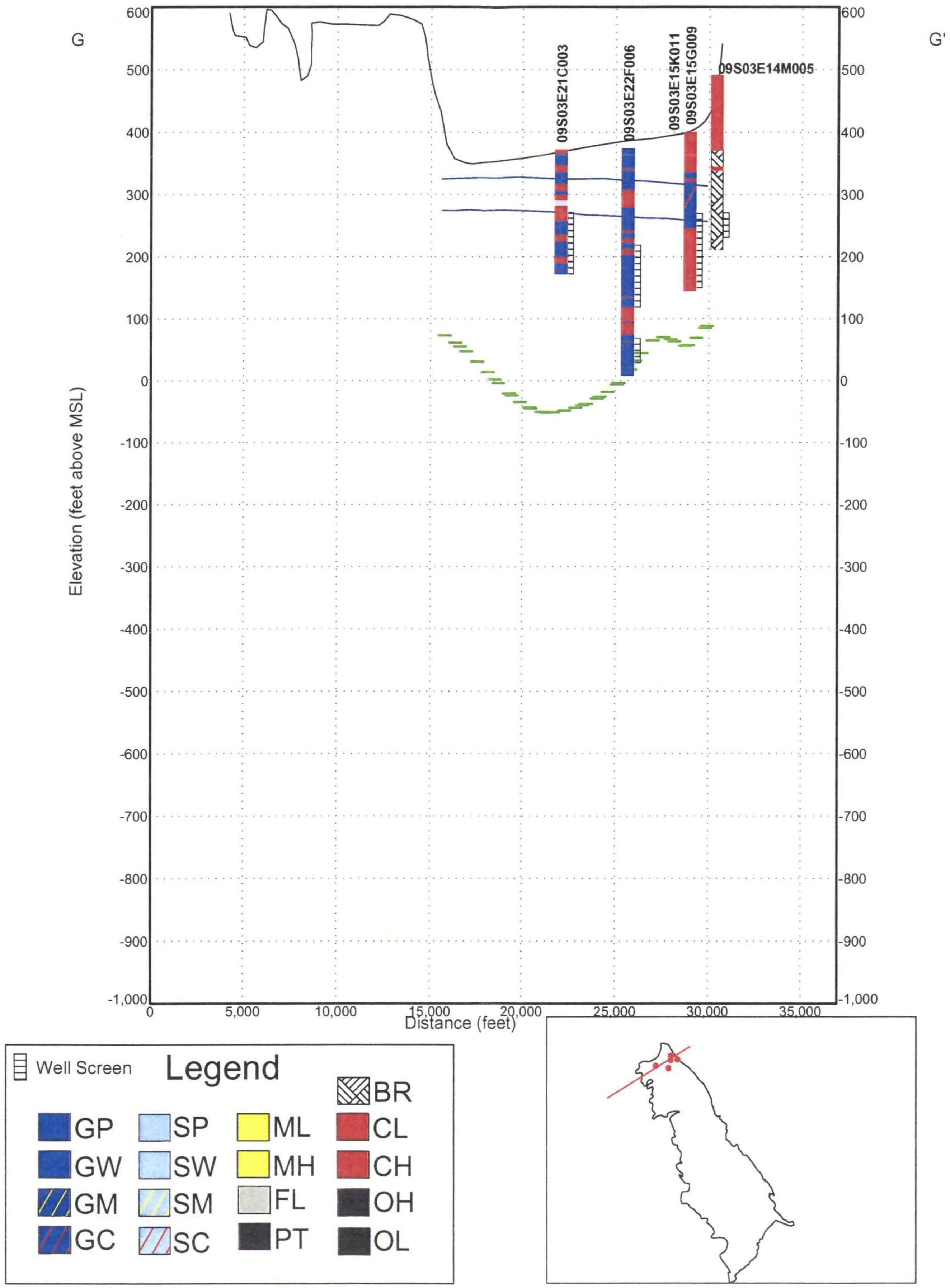


G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

XSection F-F'
Santa Clara Valley

Date: 29 Feb 04	Figure

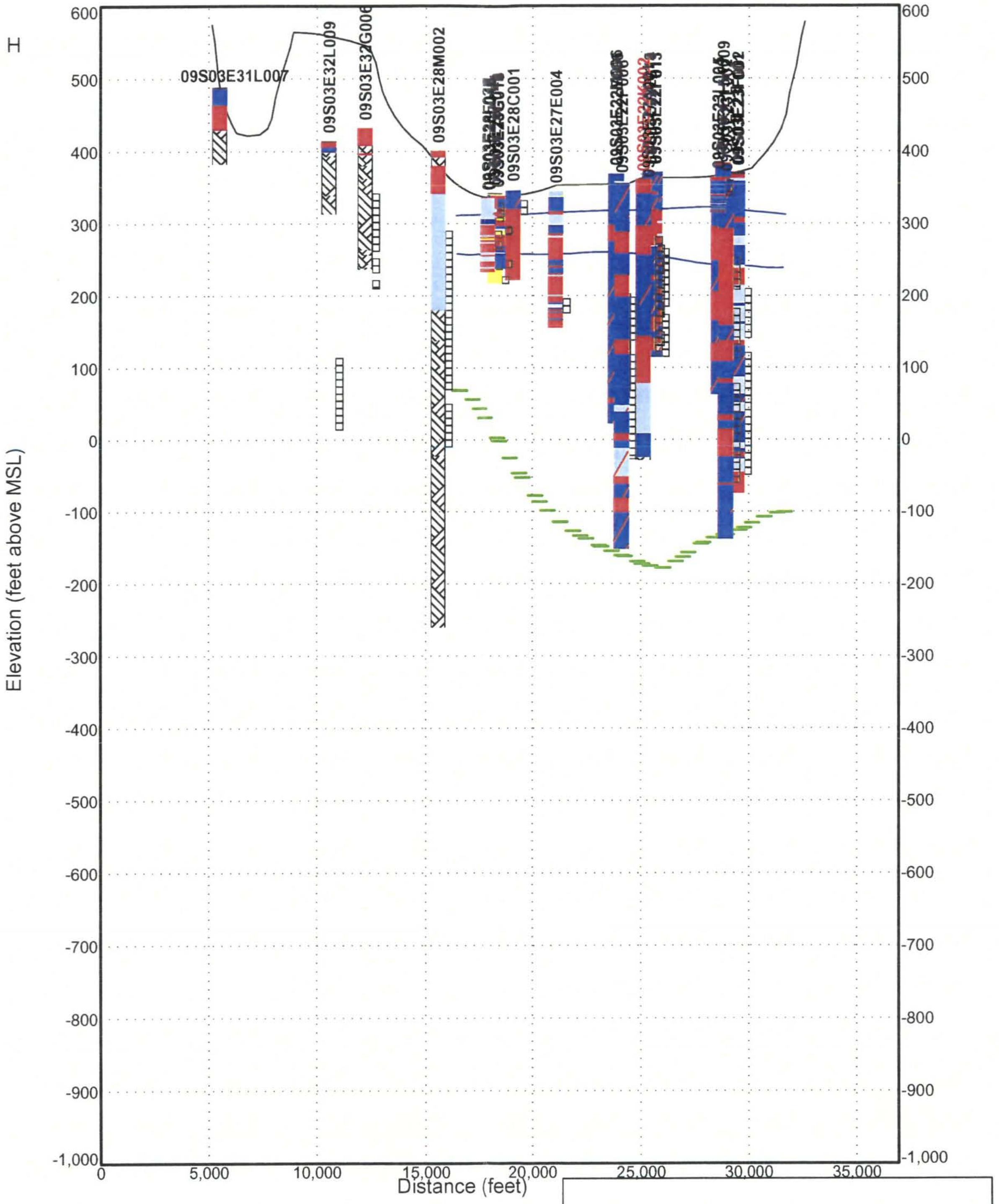
FIGURE 1-15
CROSS SECTION F-F'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL



G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

XSection G-G'	
Santa Clara Valley	
Date: 01 Mar 04	Figure

FIGURE 1-16
CROSS SECTION G-G'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL

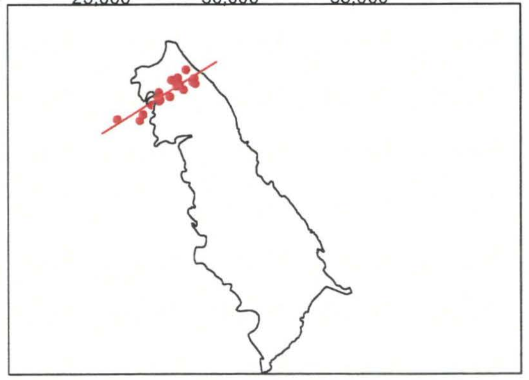


Well Screen

Legend

▨ BR

🟦 GP	SP	🟨 ML	🟥 CL
🟦 GW	SW	🟨 MH	🟥 CH
▨ GM	▨ SM	FL	⬛ OH
▨ GC	▨ SC	⬛ PT	⬛ OL



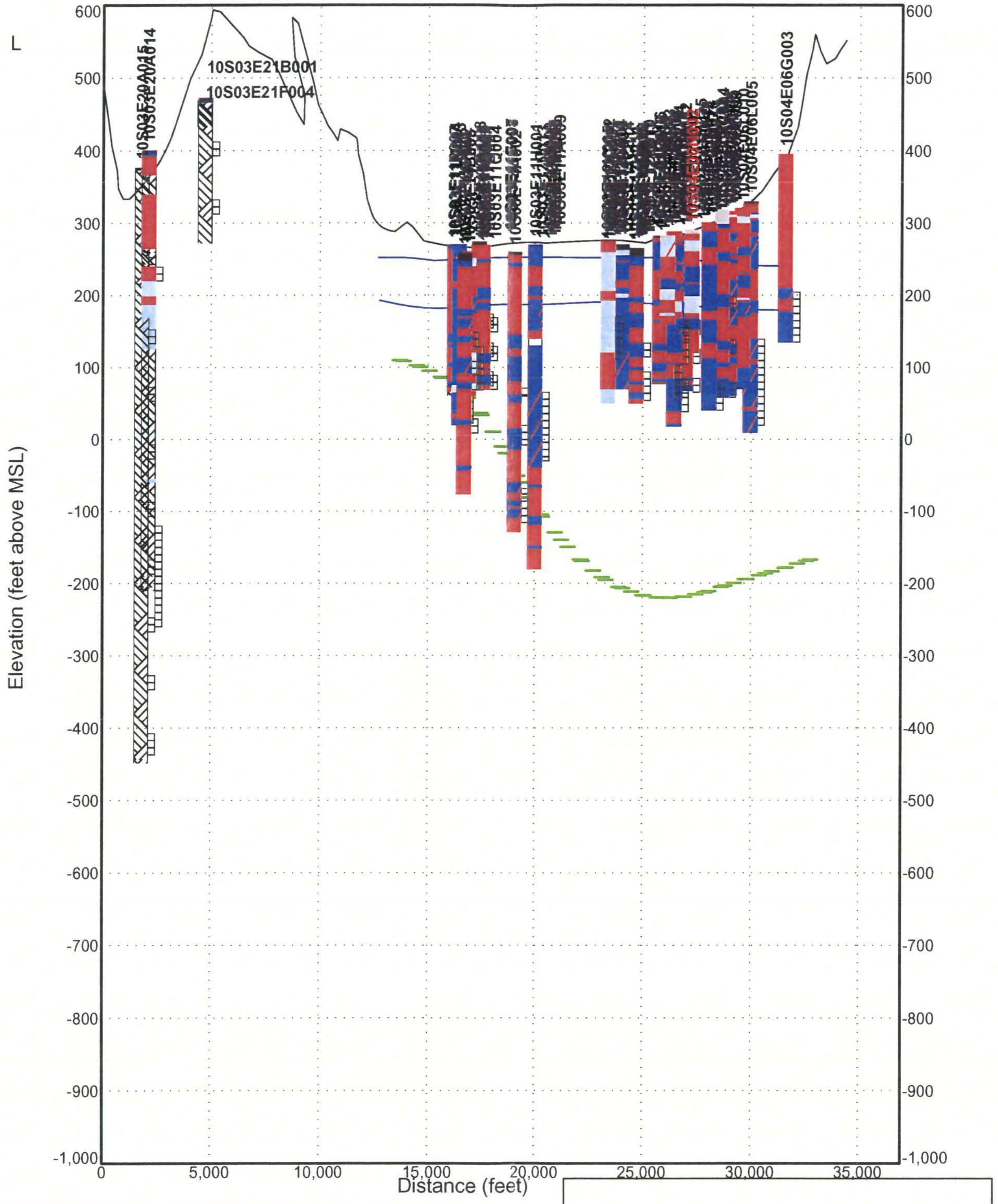
G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

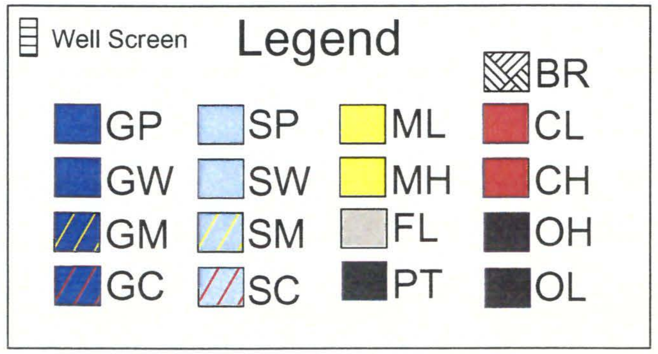
XSection H-H'	
Santa Clara Valley	
Date: 01 Mar 04	Figure

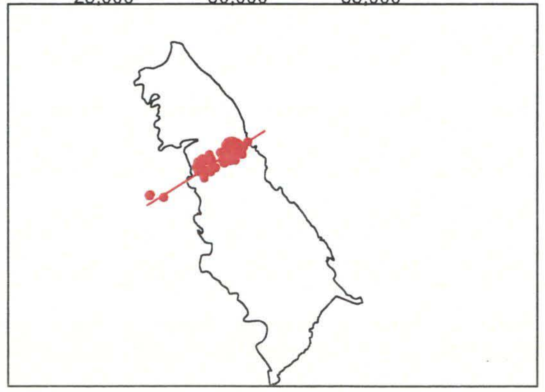
FIGURE 1-17
CROSS SECTION H-H'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 3-10_4/15/04_ccc_sfo







XSection L-L'

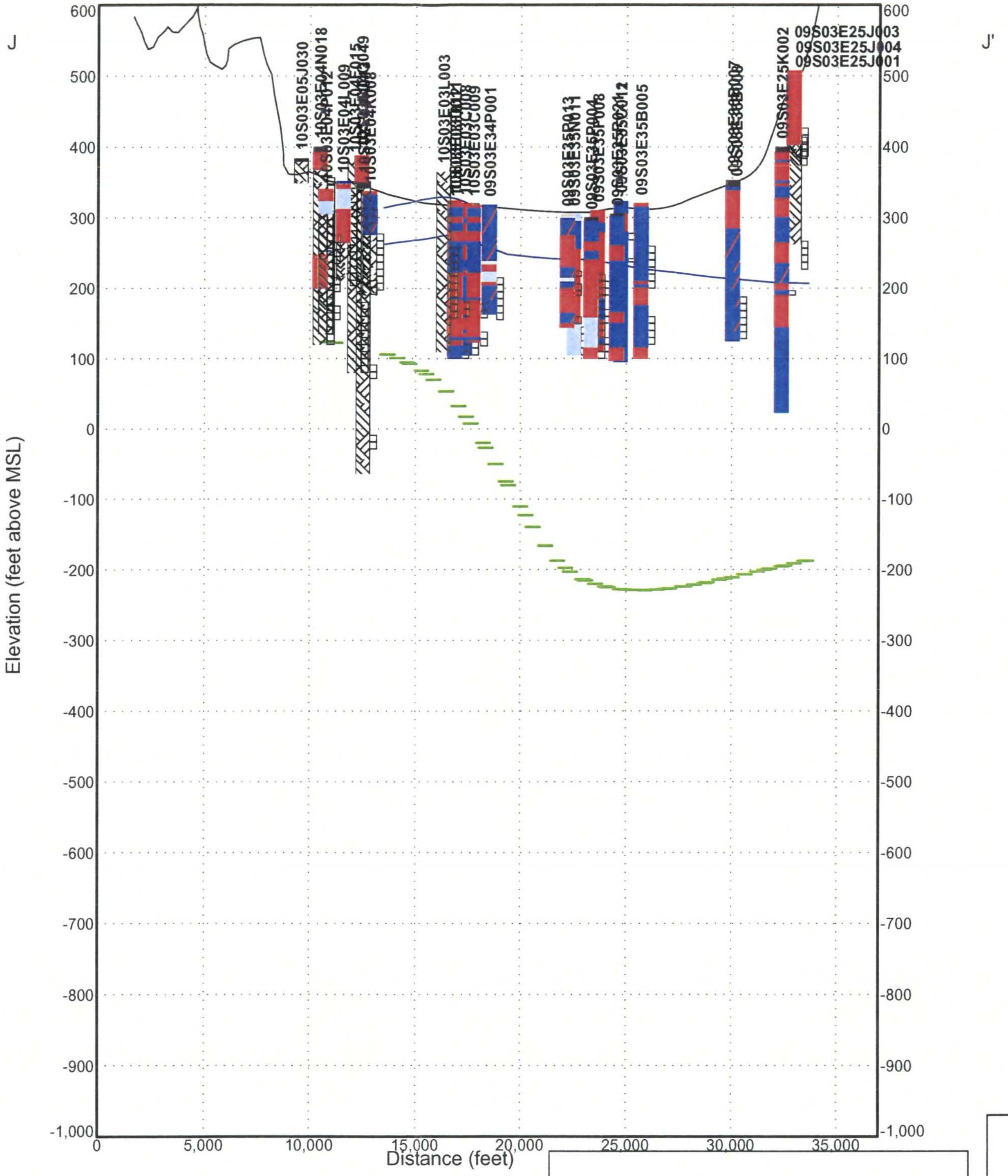
Santa Clara Valley

Date: 01 Mar 04 | Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-18
CROSS SECTION I-I'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL

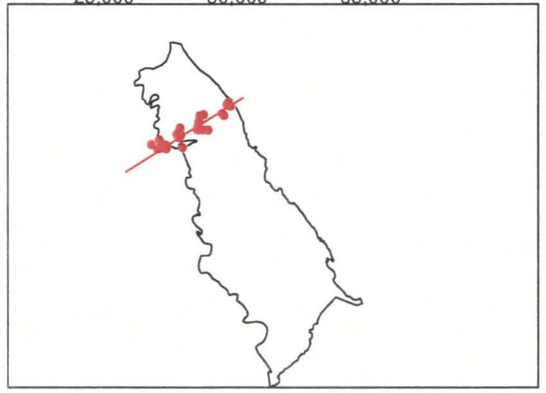
188409.LB.05 _Fig 3-11_4/15/04_ccc_sfo



▤ Well Screen

Legend

- ▨ BR
- GP
- GW
- GM
- GC
- SP
- SW
- SM
- SC
- ML
- MH
- FL
- PT
- CL
- CH
- OH
- OL



XSection J-J'

Santa Clara Valley

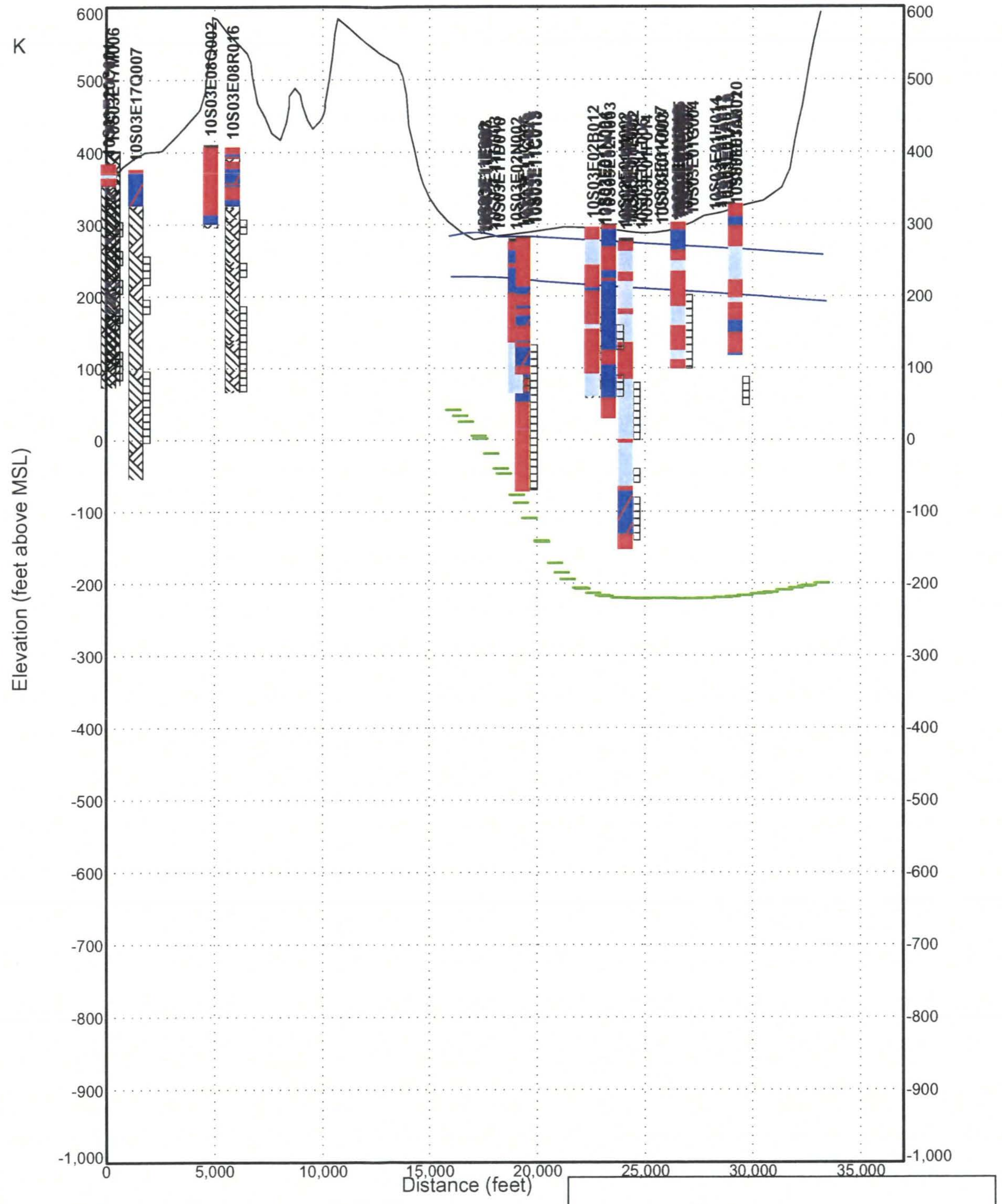
Date: 01 Mar 04

Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-19
CROSS SECTION J-J'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

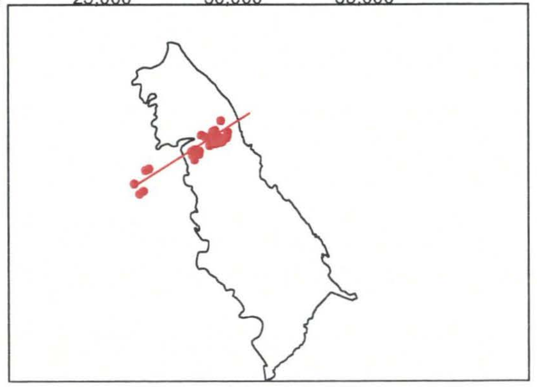
CH2MHILL



▤ Well Screen

Legend

- ▨ BR
- 🟦 GP
- 🟦 SP
- 🟨 ML
- 🟥 CL
- 🟦 GW
- 🟦 SW
- 🟨 MH
- 🟥 CH
- ▨ GM
- ▨ SM
- ⬜ FL
- ⬛ OH
- ▨ GC
- ▨ SC
- ⬛ PT
- ⬛ OL



XSection K-K'
Santa Clara Valley

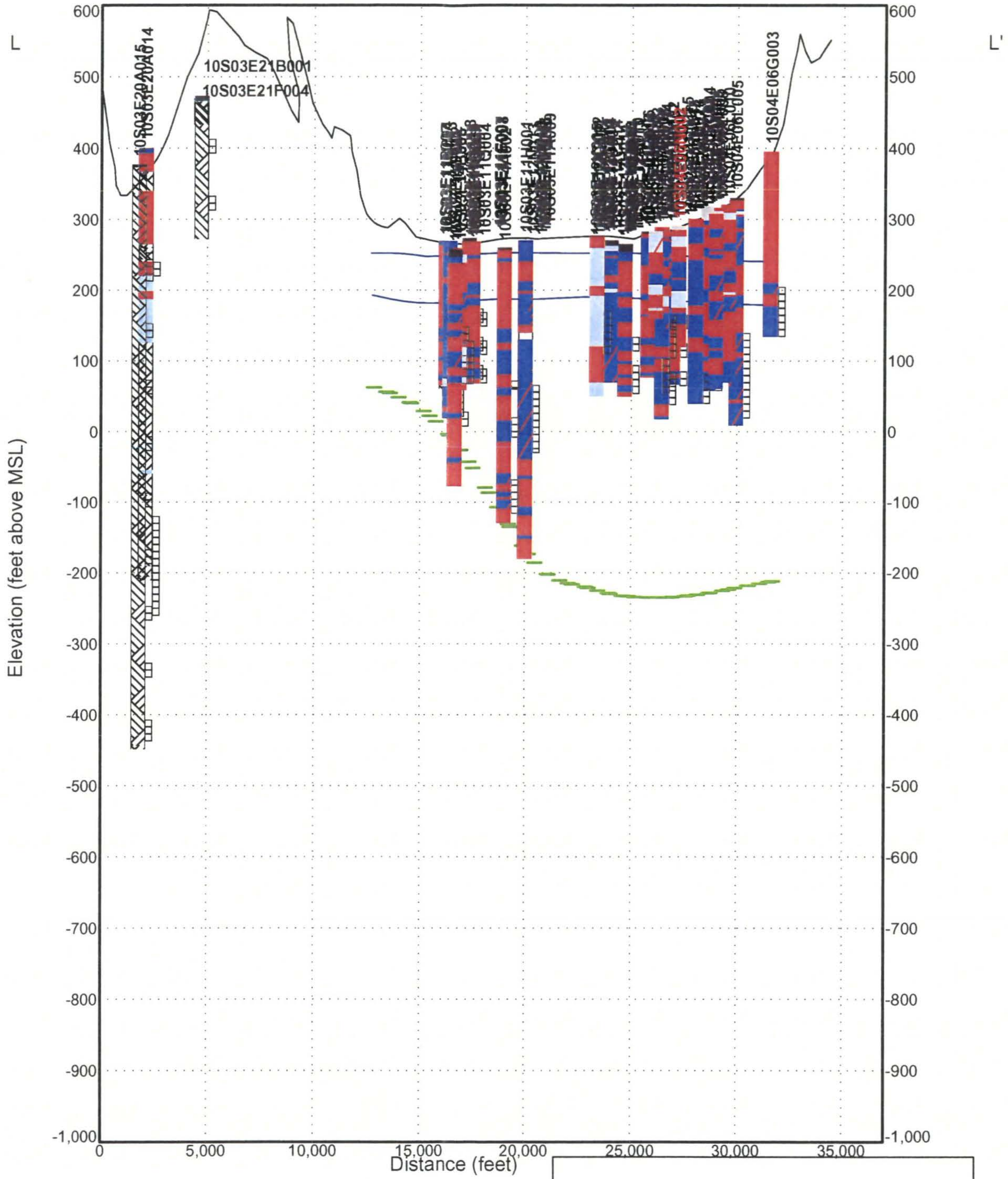
Date: 01 Mar 04 | Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-20
CROSS SECTION K-K'

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

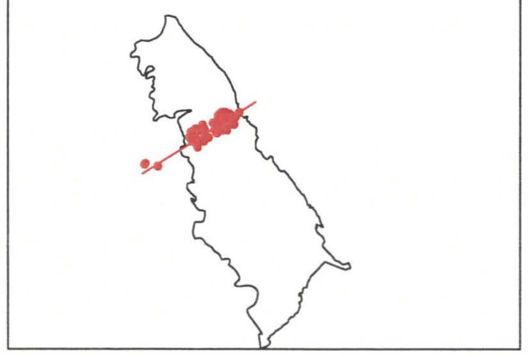
CH2MHILL



☰ Well Screen

Legend

			▨ BR
🟦 GP	🟦 SP	🟨 ML	🟥 CL
🟦 GW	🟦 SW	🟨 MH	🟥 CH
▨ GM	▨ SM	⬜ FL	⬛ OH
▨ GC	▨ SC	⬛ PT	⬛ OL

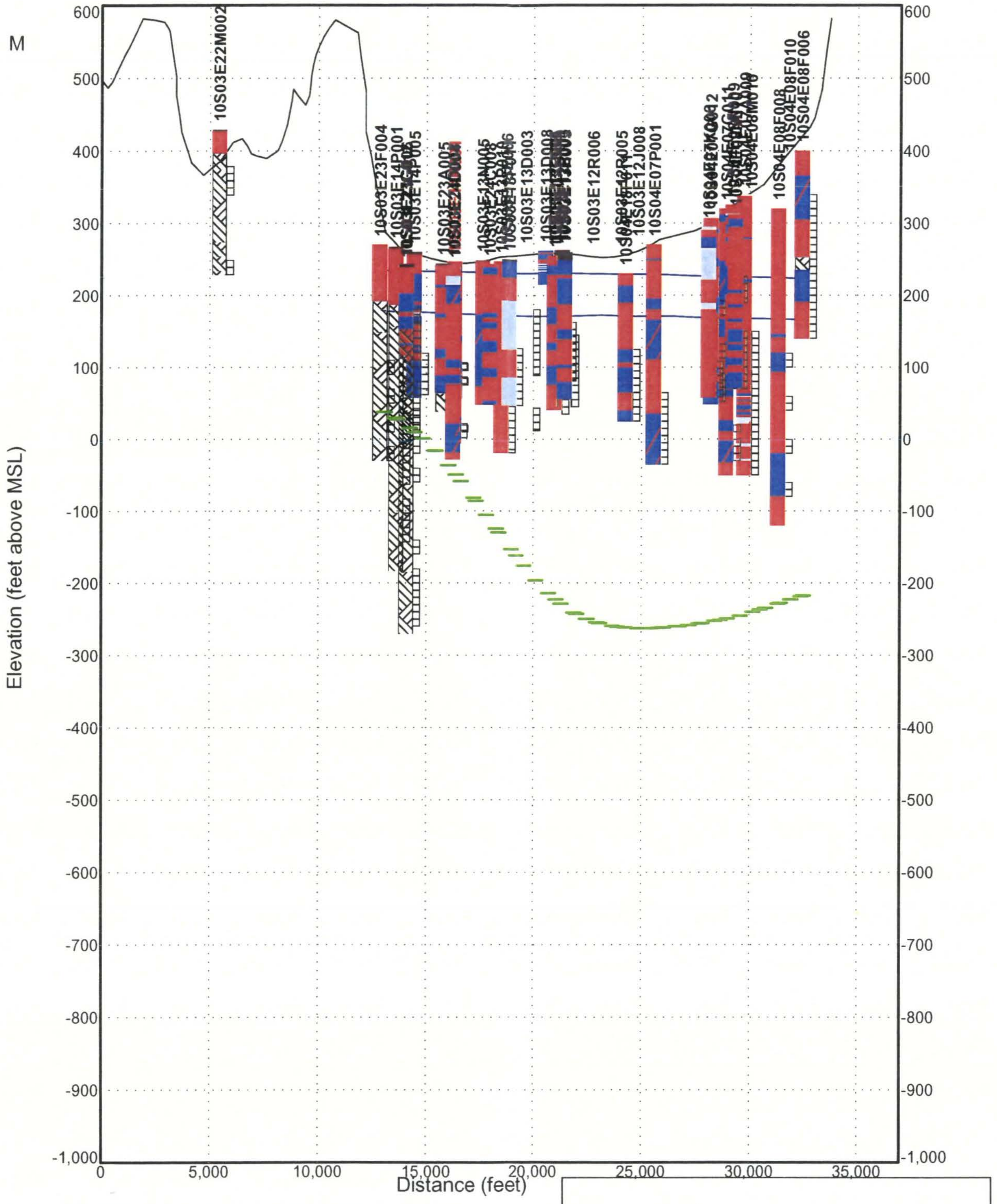


XSection L-L'
Santa Clara Valley
Date: 01 Mar 04	Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-21
CROSS SECTION L-L'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

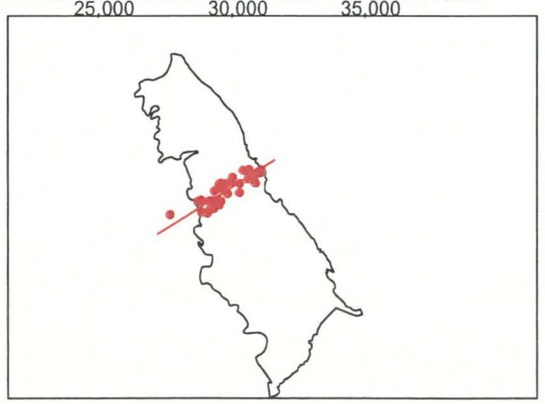
CH2MHILL



Well Screen

Legend

- ▨ BR
- GP
- SP
- ML
- CL
- GW
- SW
- MH
- CH
- GM
- SM
- FL
- OH
- GC
- SC
- PT
- OL



XSection M-M'

Santa Clara Valley

Date: 01 Mar 04

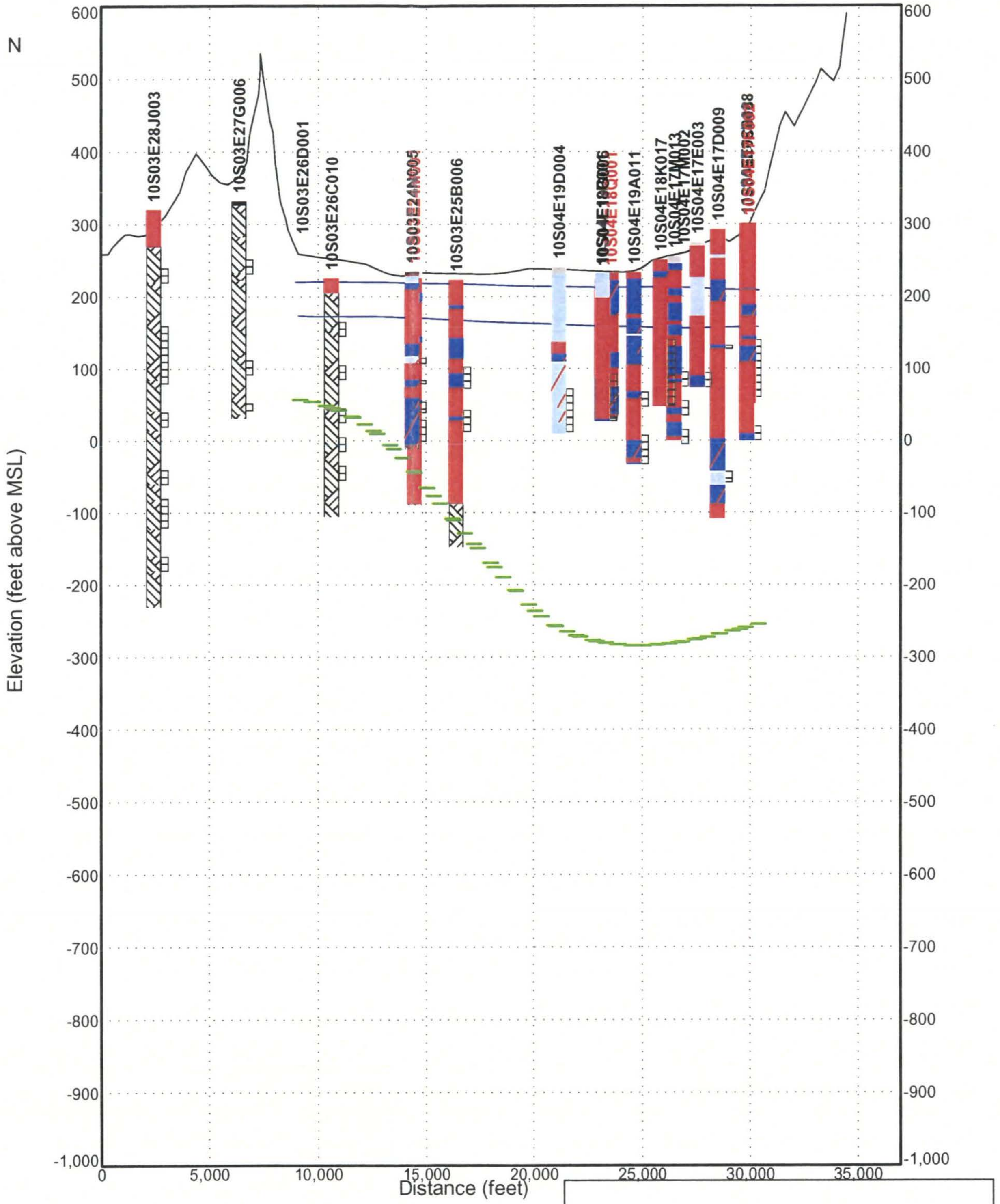
Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-22
CROSS SECTION M-M'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

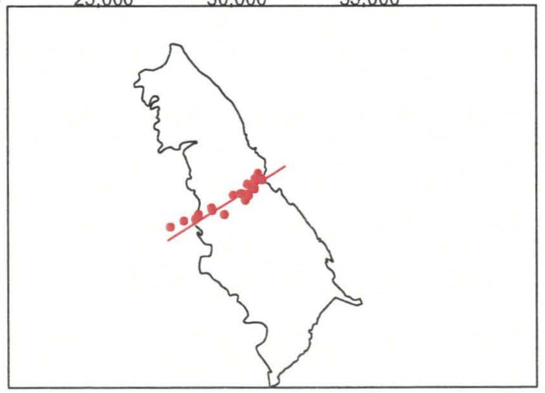
188409.LB.05 _Fig 3-15_4/15/04_ccc_sfo



Well Screen

Legend

			▨ BR
GP	SP	ML	CL
GW	SW	MH	CH
GM	SM	FL	OH
GC	SC	PT	OL



XSection N-N'

Santa Clara Valley

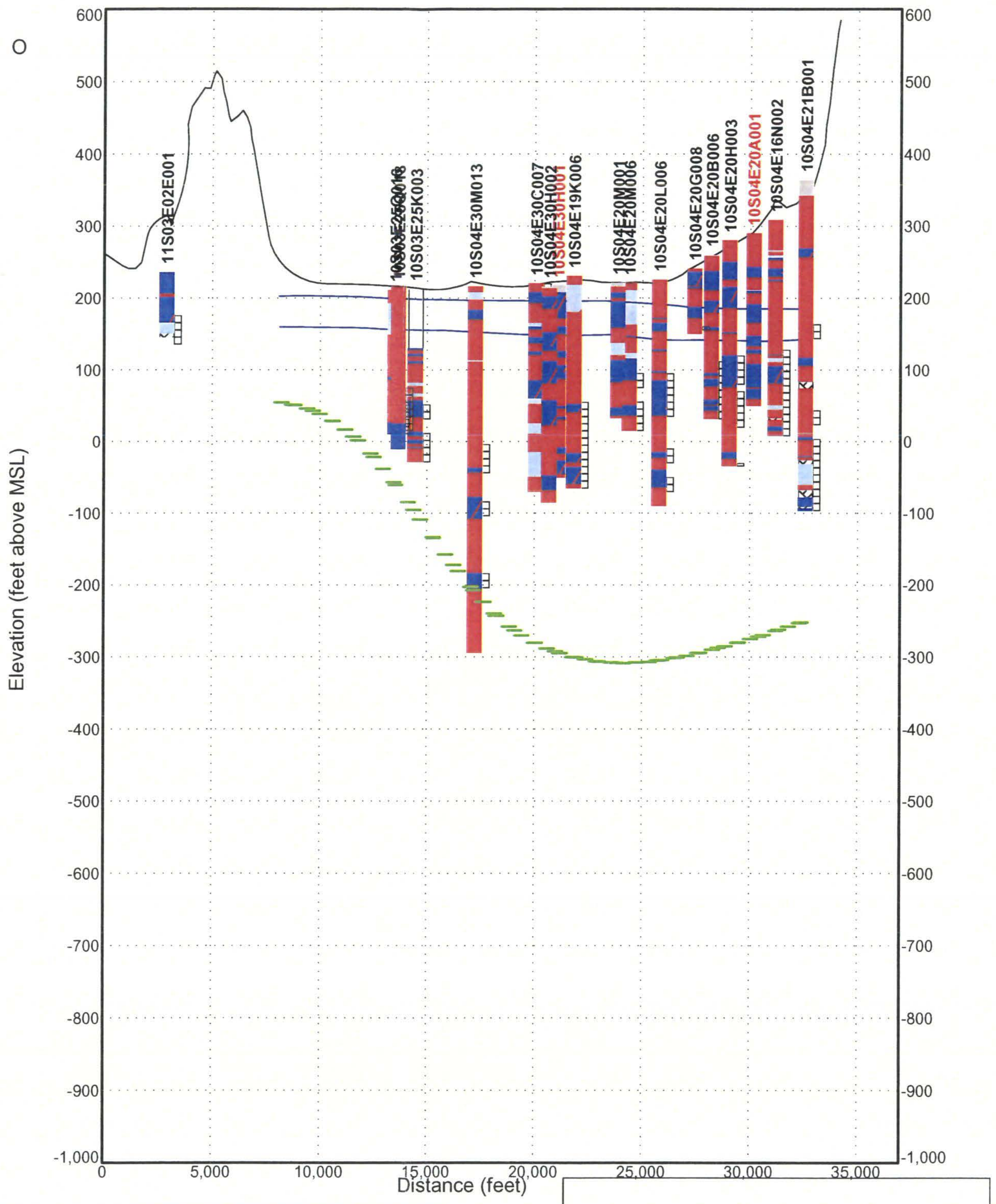
Date: 01 Mar 04

Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-23
CROSS SECTION N-N'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

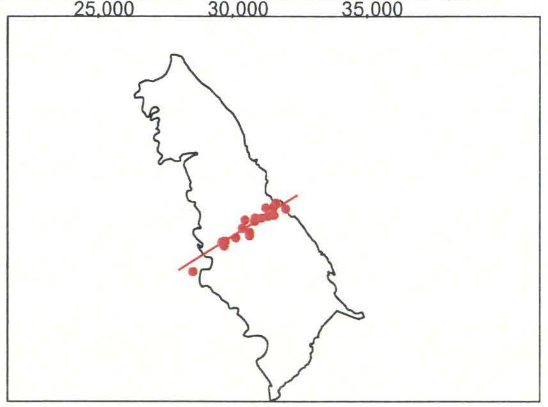
CH2MHILL



Legend

Well Screen

			▨ BR
■ GP	■ SP	■ ML	■ CL
■ GW	■ SW	■ MH	■ CH
▨ GM	▨ SM	■ FL	■ OH
▨ GC	▨ SC	■ PT	■ OL



XSection O-O'

Santa Clara Valley

Date: 01 Mar 04

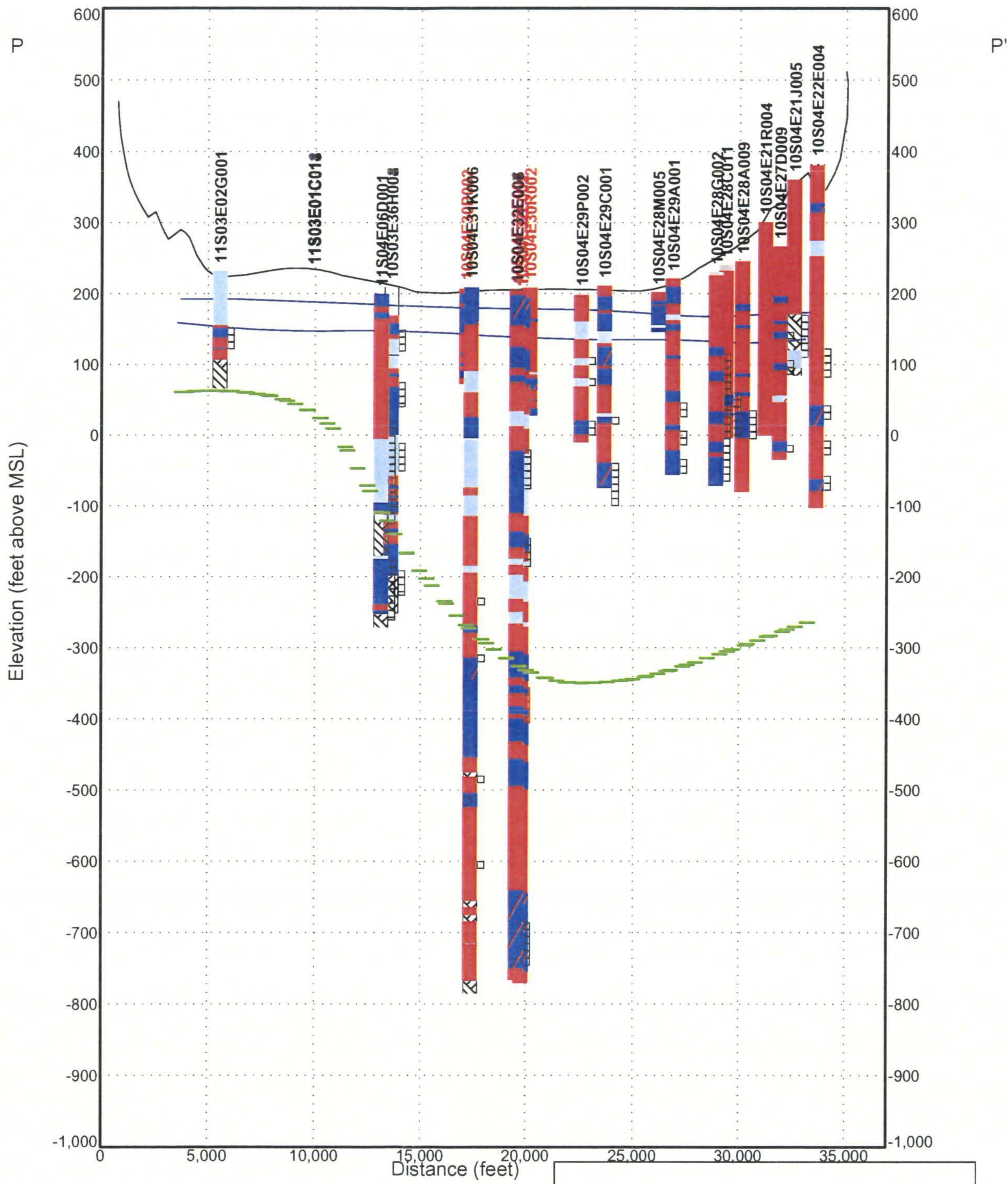
Figure

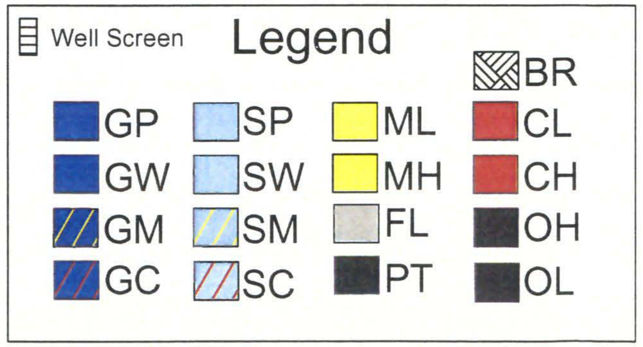
G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

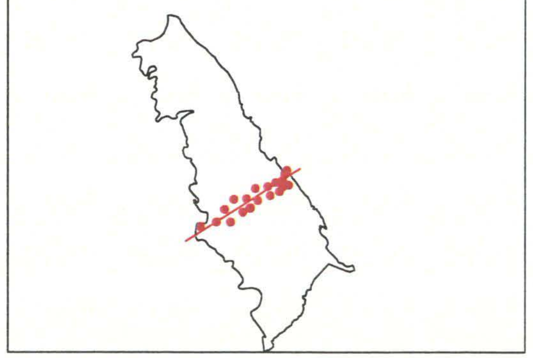
FIGURE 1-24
CROSS SECTION O-O'

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL







G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/1/2004

XSection P-P'

Santa Clara Valley

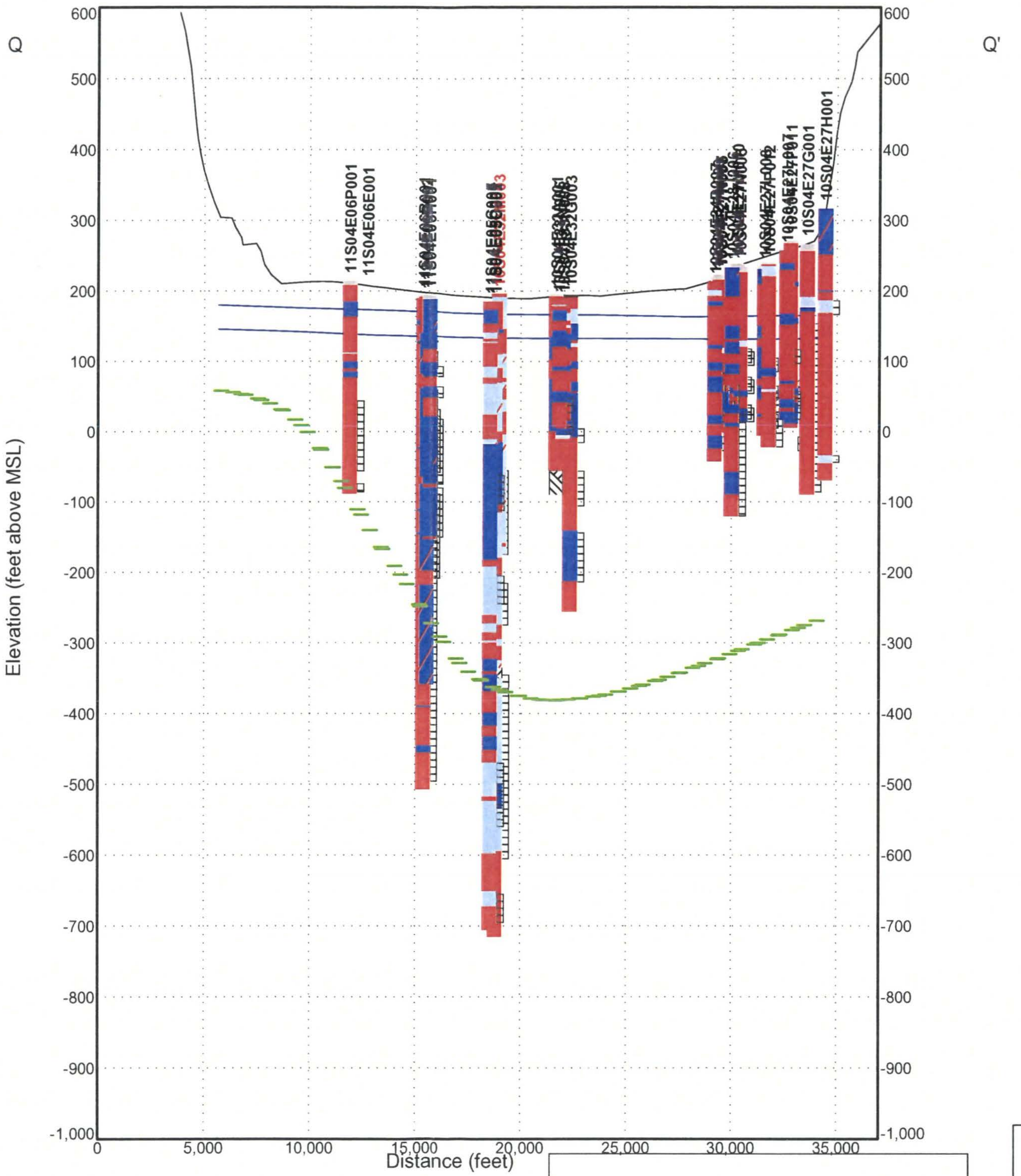
Date: 01 Mar 04 | Figure

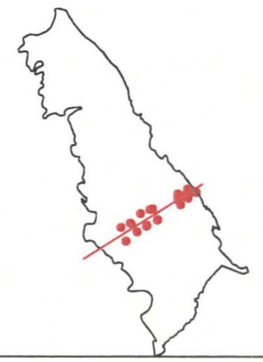
FIGURE 1-25
CROSS SECTION P-P'

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 3-18_4/15/04_ccc_sfo





XSection Q-Q'

Santa Clara Valley

Date: 01 Mar 04

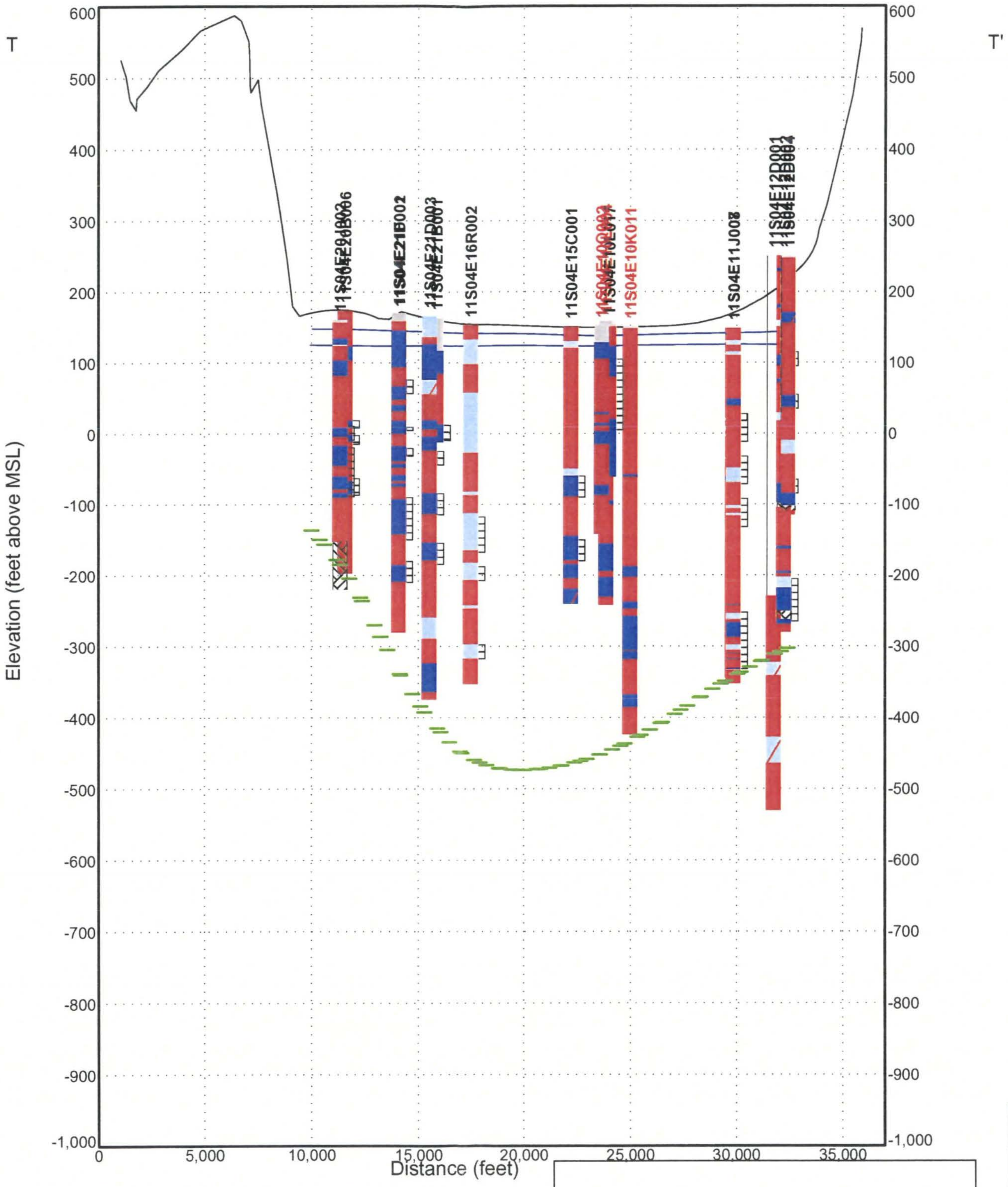
Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-26
CROSS SECTION Q-Q'

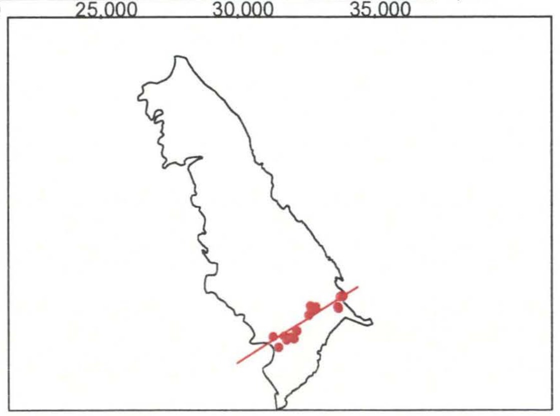
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Legend

☰ Well Screen			▨ BR
■ GP	■ SP	■ ML	■ CL
■ GW	■ SW	■ MH	■ CH
▨ GM	▨ SM	■ FL	■ OH
▨ GC	▨ SC	■ PT	■ OL



XSection T-T'

Santa Clara Valley

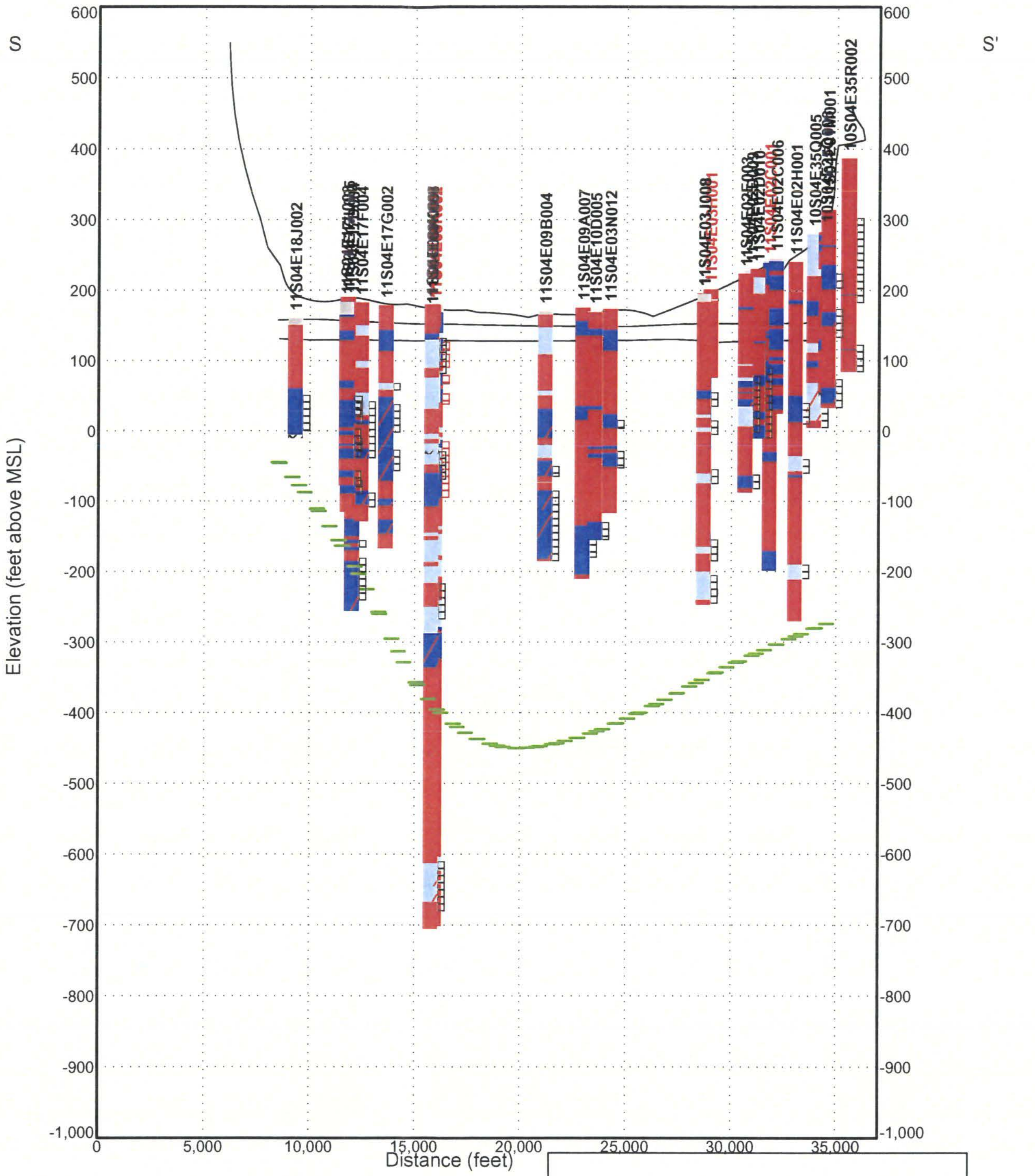
Date: 01 Mar 04

Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-27
CROSS SECTION R-R'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL

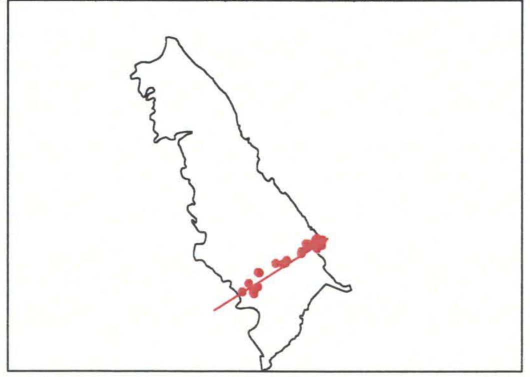
188409.LB.05 _Fig 3-20_4/15/04_ccc_sfo



Legend

☰ Well Screen

			▨ BR
■ GP	■ SP	■ ML	■ CL
■ GW	■ SW	■ MH	■ CH
▨ GM	▨ SM	■ FL	■ OH
▨ GC	▨ SC	■ PT	■ OL

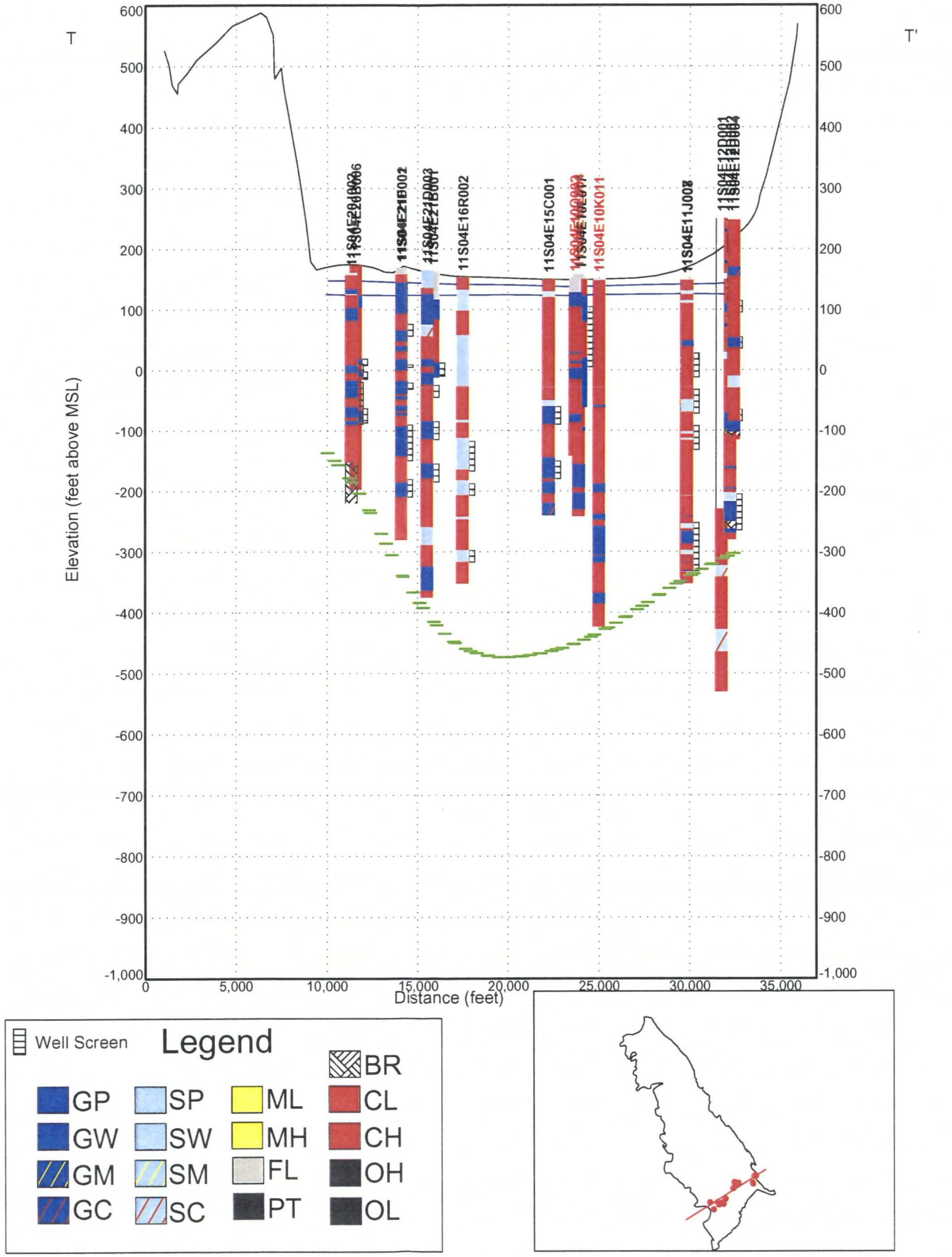


G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

XSection S-S'	
Santa Clara Valley	
Date: 01 Mar 04	Figure

FIGURE 1-28
CROSS SECTION S-S'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



XSection T-T'

Santa Clara Valley

Date: 01 Mar 04

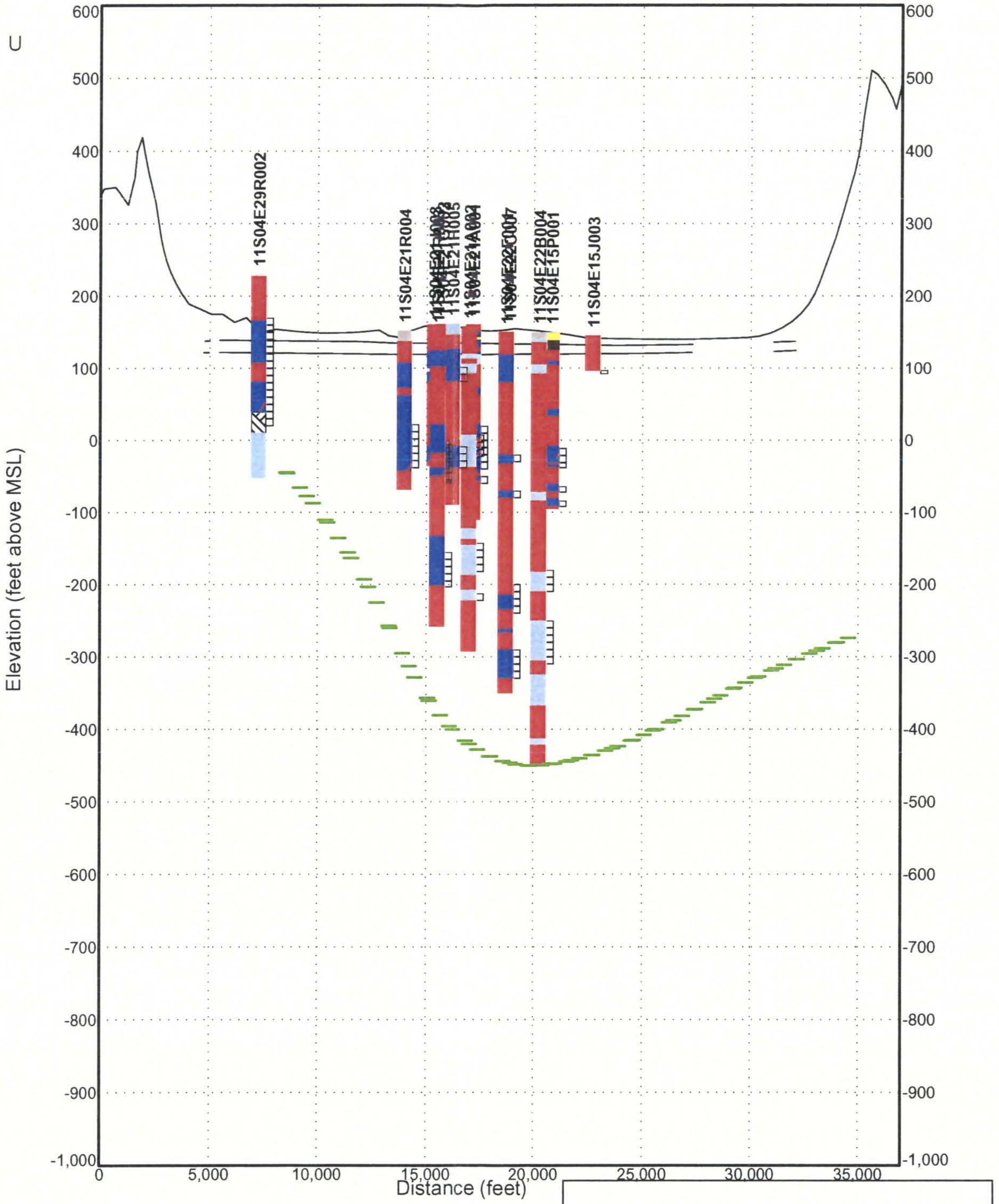
Figure

G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

FIGURE 1-29
CROSS SECTION T-T'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

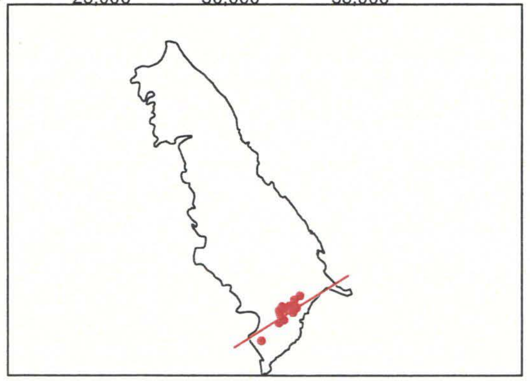
CH2MHILL

188409.LB.05 _Fig 3-22_4/15/04_ccc_sfo



Legend

- ▤ Well Screen
- ▨ BR
- 🟦 GP
- 🟦 GW
- ▨ GM
- ▨ GC
- 🟦 SP
- 🟦 SW
- ▨ SM
- ▨ SC
- 🟨 ML
- 🟨 MH
- ⬜ FL
- ⬛ PT
- 🟥 CL
- 🟥 CH
- ⬛ OH
- ⬛ OL



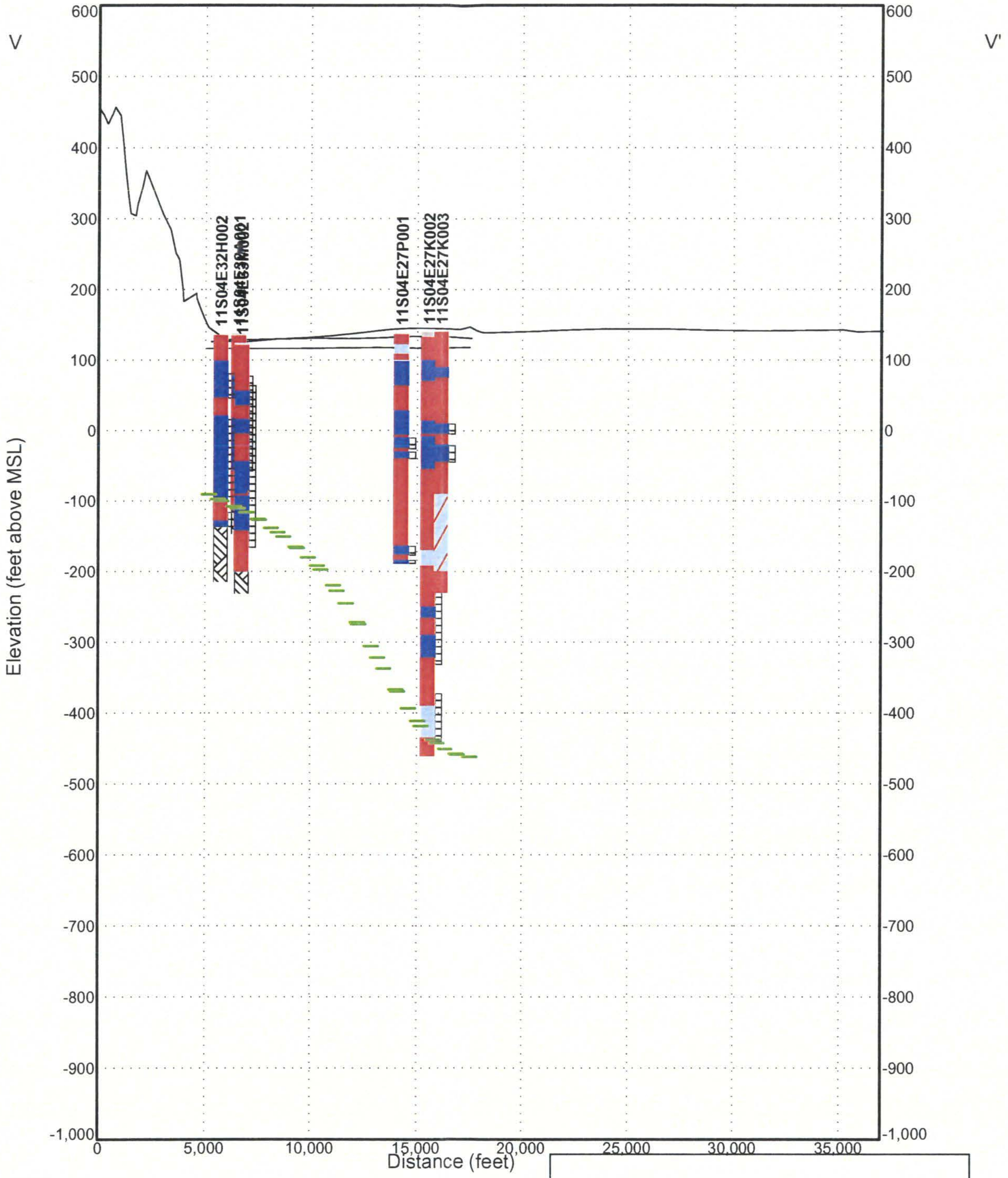
G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

XSection U-U'
Santa Clara Valley
Date: 01 Mar 04 | Figure

FIGURE 1-30
CROSS SECTION U-U'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 3-23_4/15/04_ccc_sfo

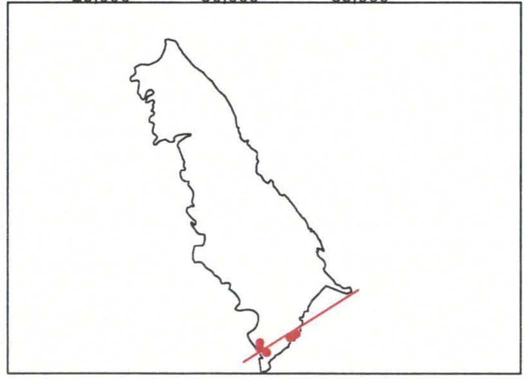


Legend

▤ Well Screen

▨ BR

■ GP	■ SP	■ ML	■ CL
■ GW	■ SW	■ MH	■ CH
▨ GM	▨ SM	■ FL	■ OH
▨ GC	▨ SC	■ PT	■ OL



G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_SHORT
3/19/2004

XSection V-V'

Santa Clara Valley

Date: 01 Mar 04 | Figure

FIGURE 1-31
CROSS SECTION V-V'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

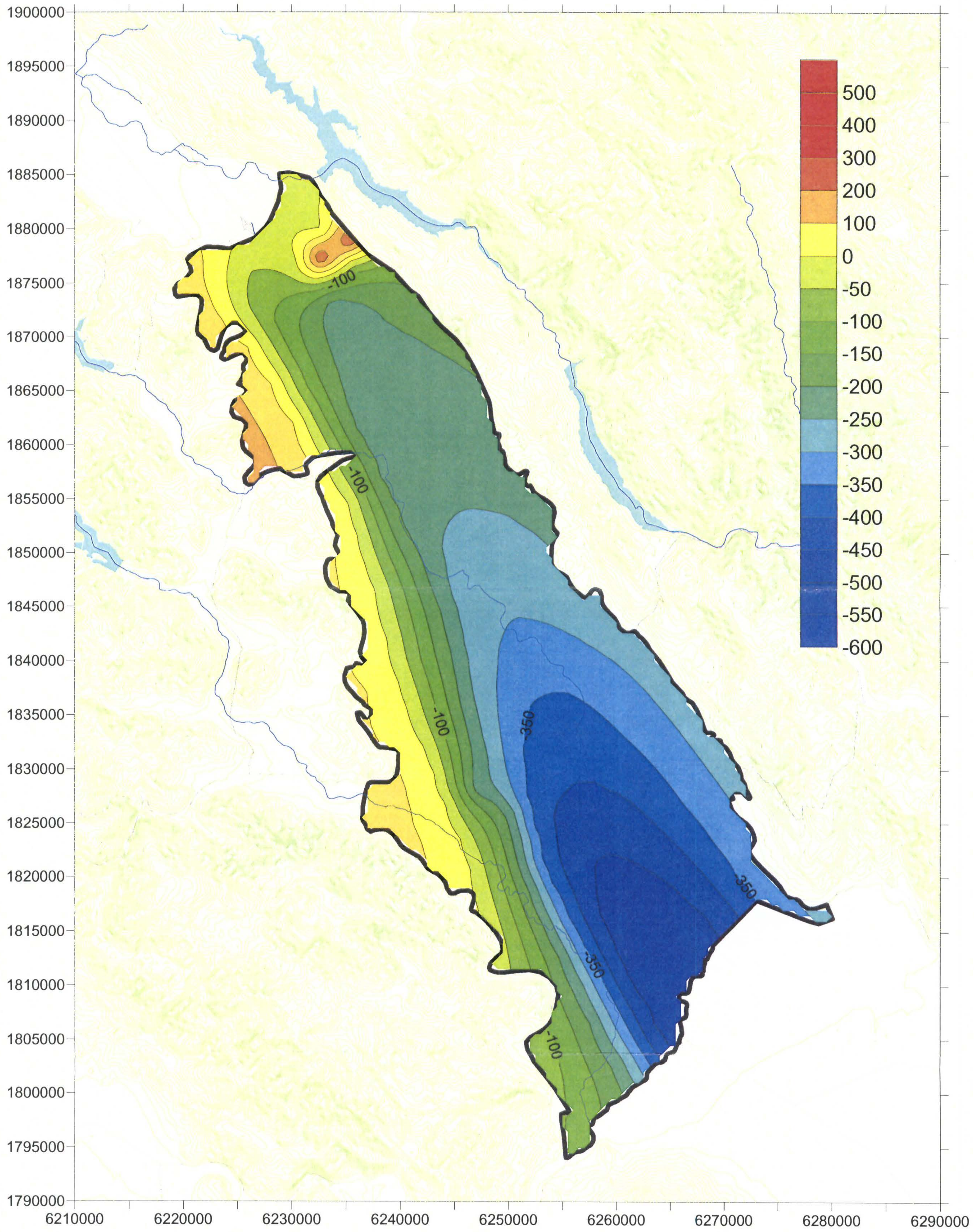


FIGURE 1-32
BEDROCK ELEVATION
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

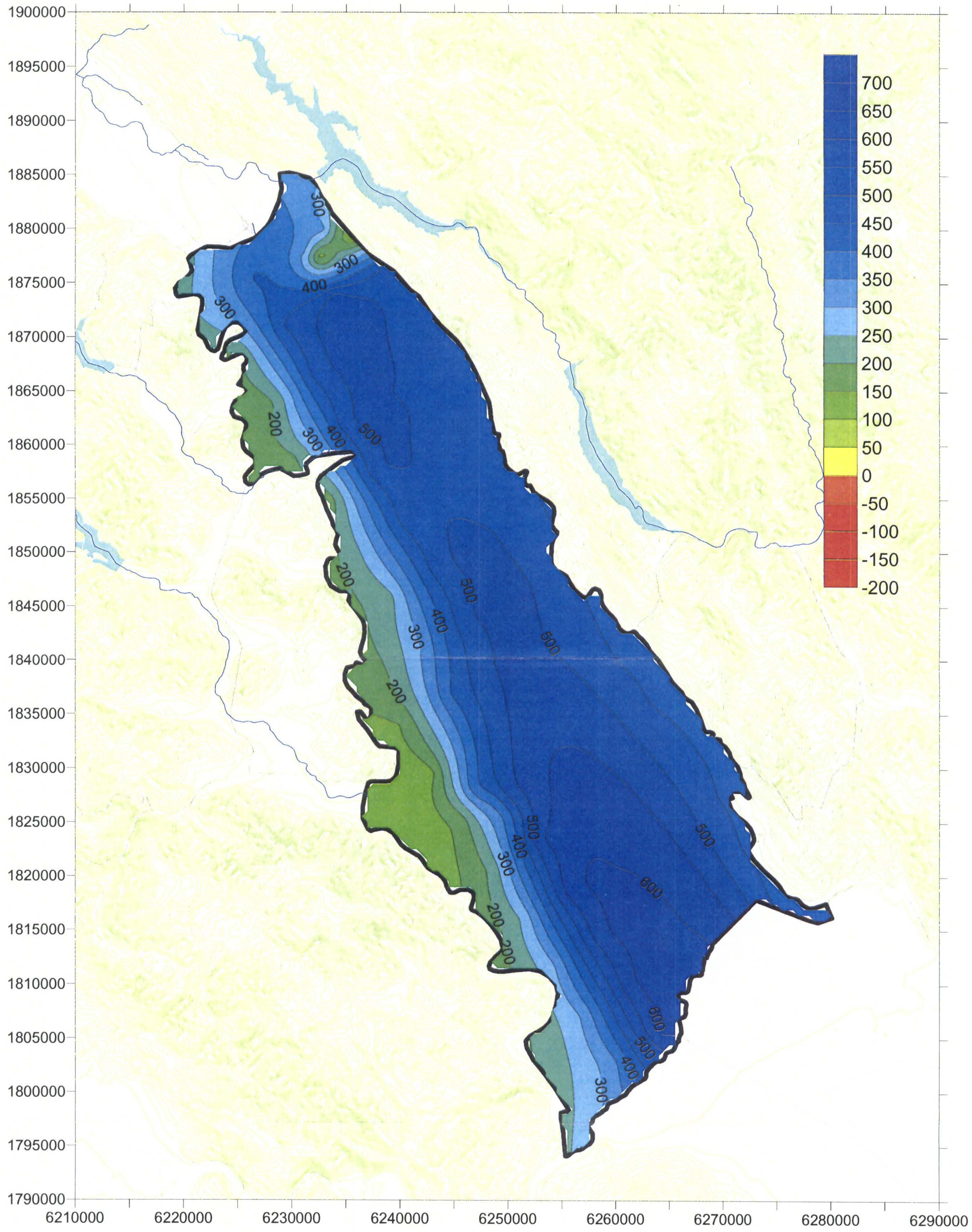


FIGURE 1-33
SATURATED THICKNESS (STEADY STATE PERIOD 1996-98)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

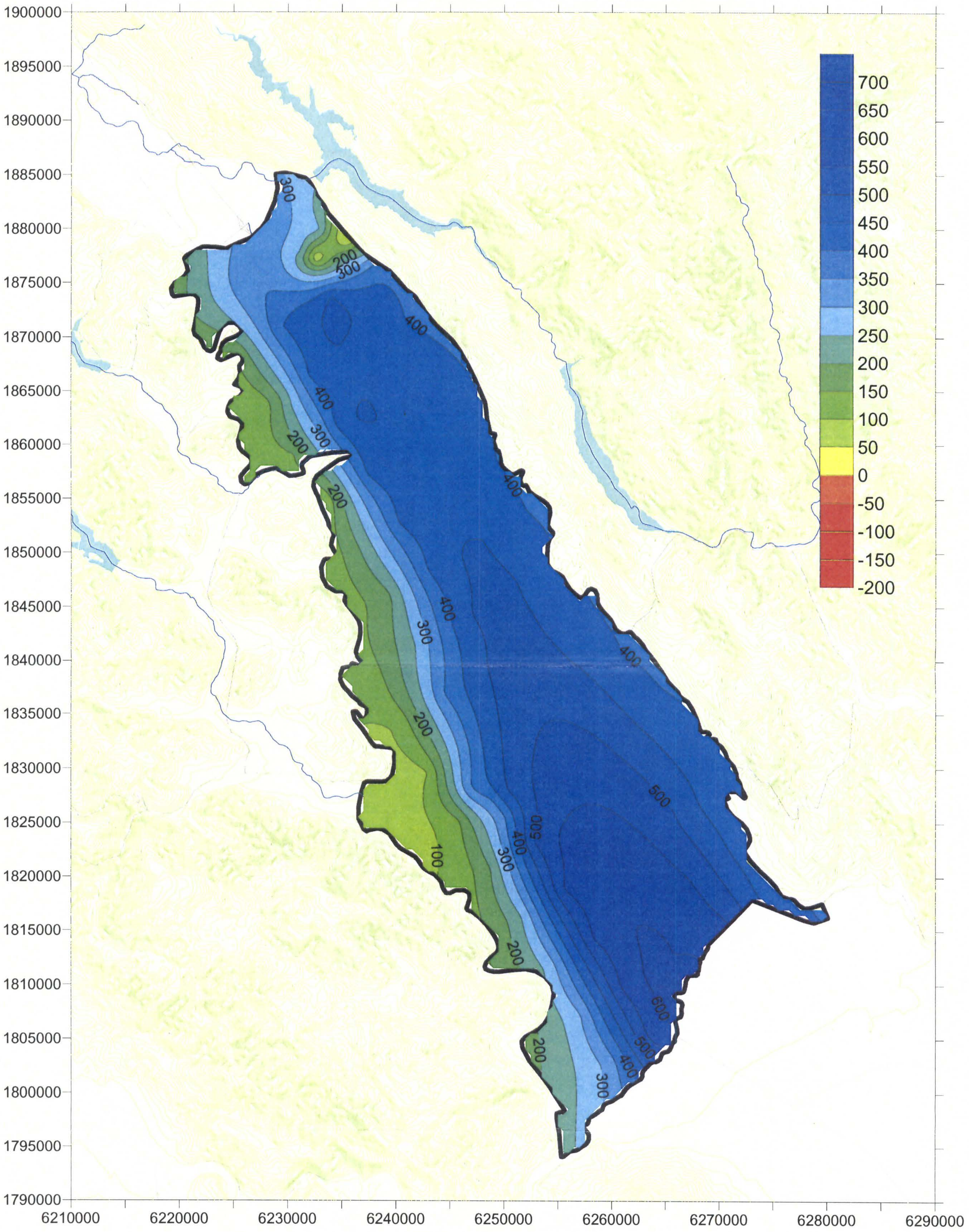


FIGURE 1-34
SATURATED THICKNESS
(LOW WATER LEVEL PERIOD 1989-1990)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

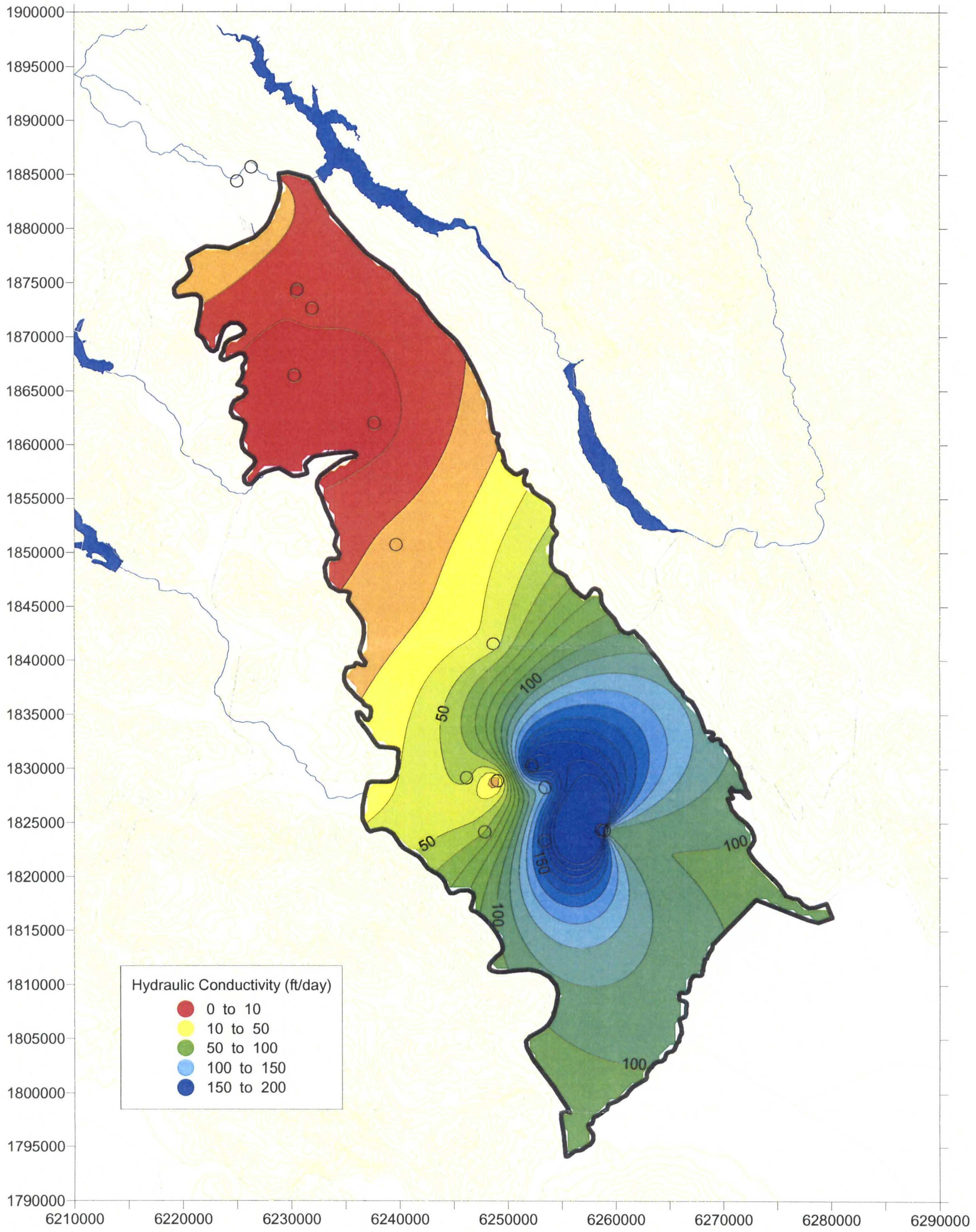


FIGURE 1-35
HYDRAULIC CONDUCTIVITY
(ESTIMATED FROM SPECIFIC CAPACITY)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

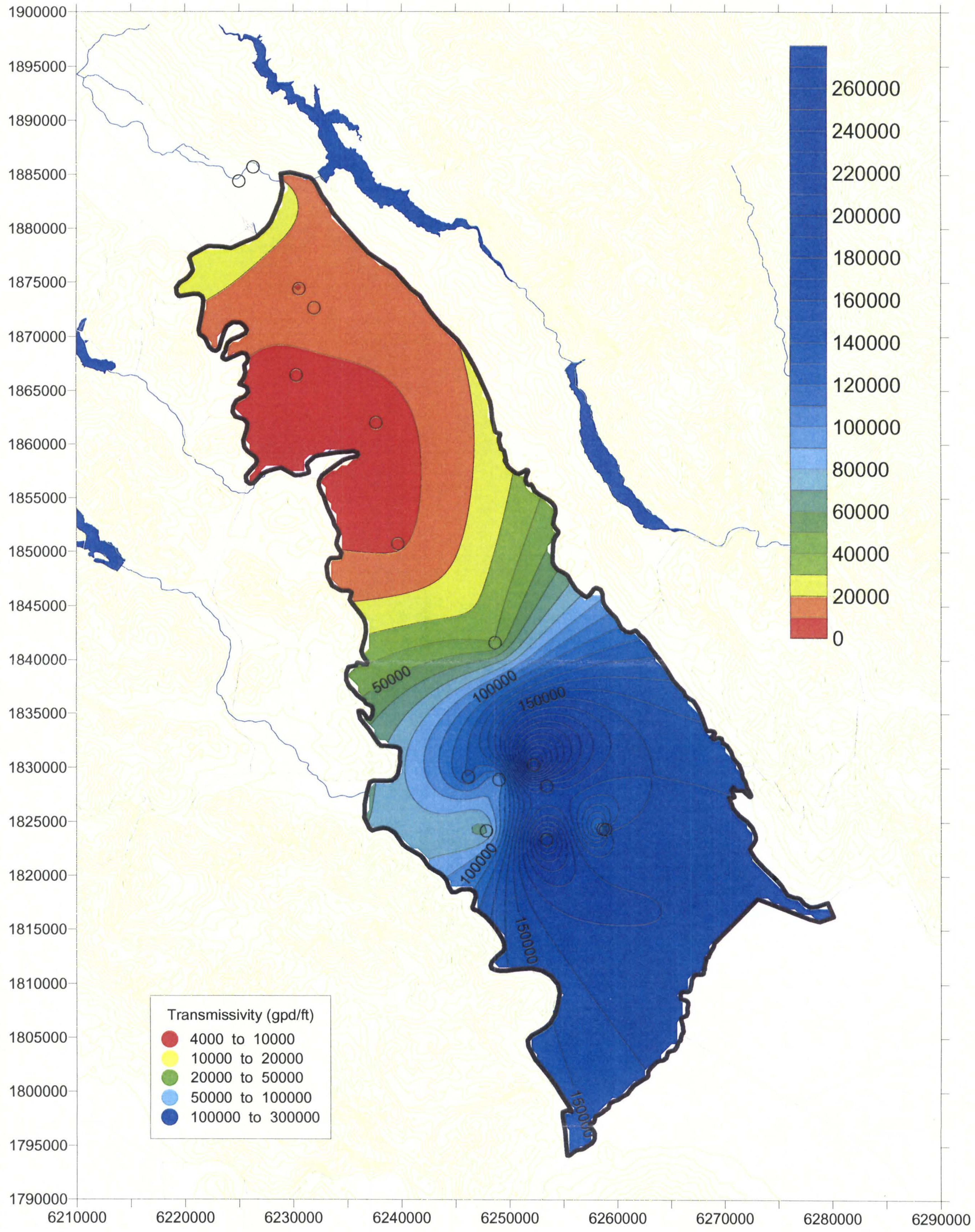


FIGURE 1-36
TRANSMISSIVITY (ESTIMATED FROM SPECIFIC CAPACITY)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409.LB.05_Fig 3-29_4/15/04_ccc_sfo

CH2MHILL

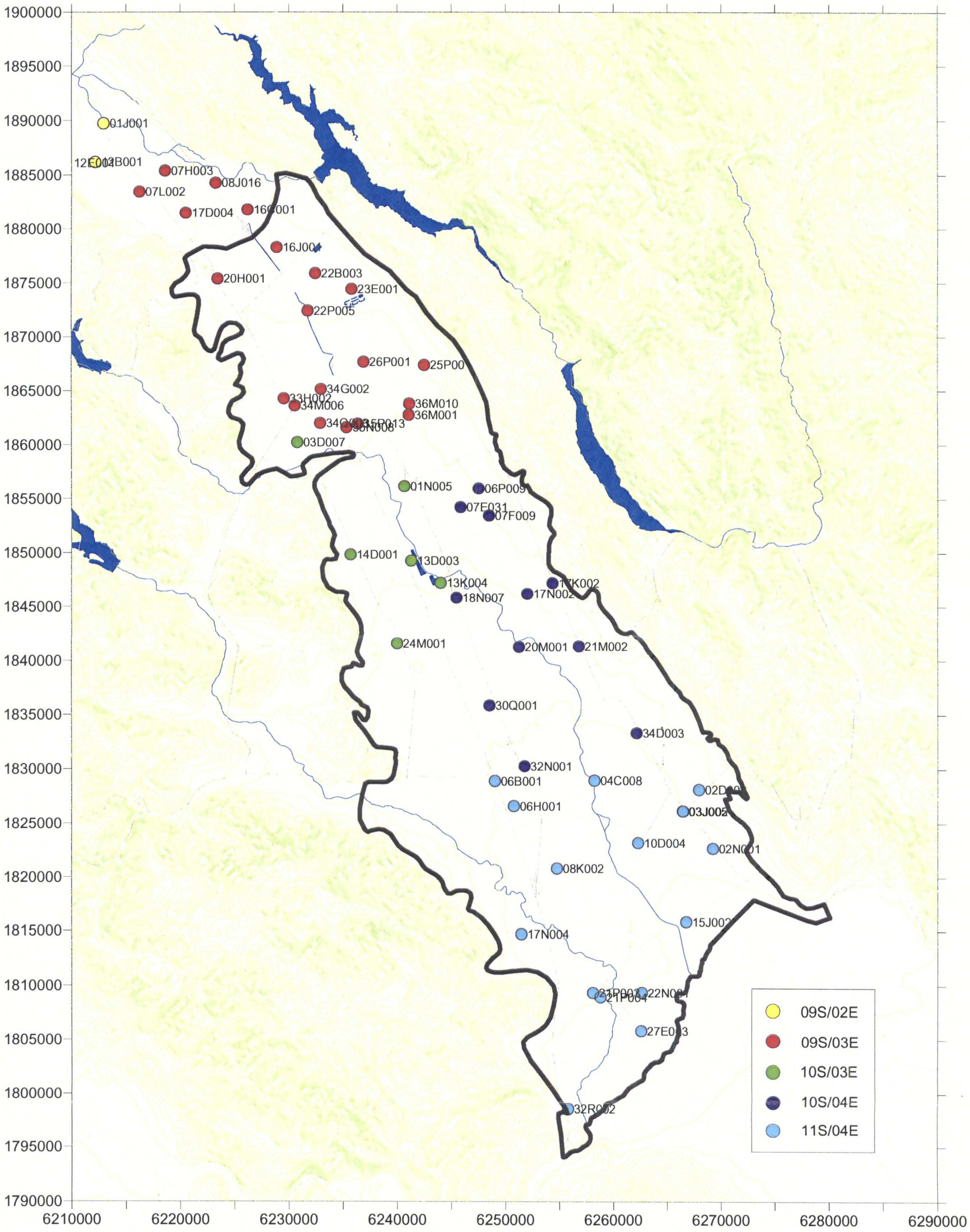


FIGURE 1-37
LOCATION OF WELLS WITH WATER LEVEL DATA

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

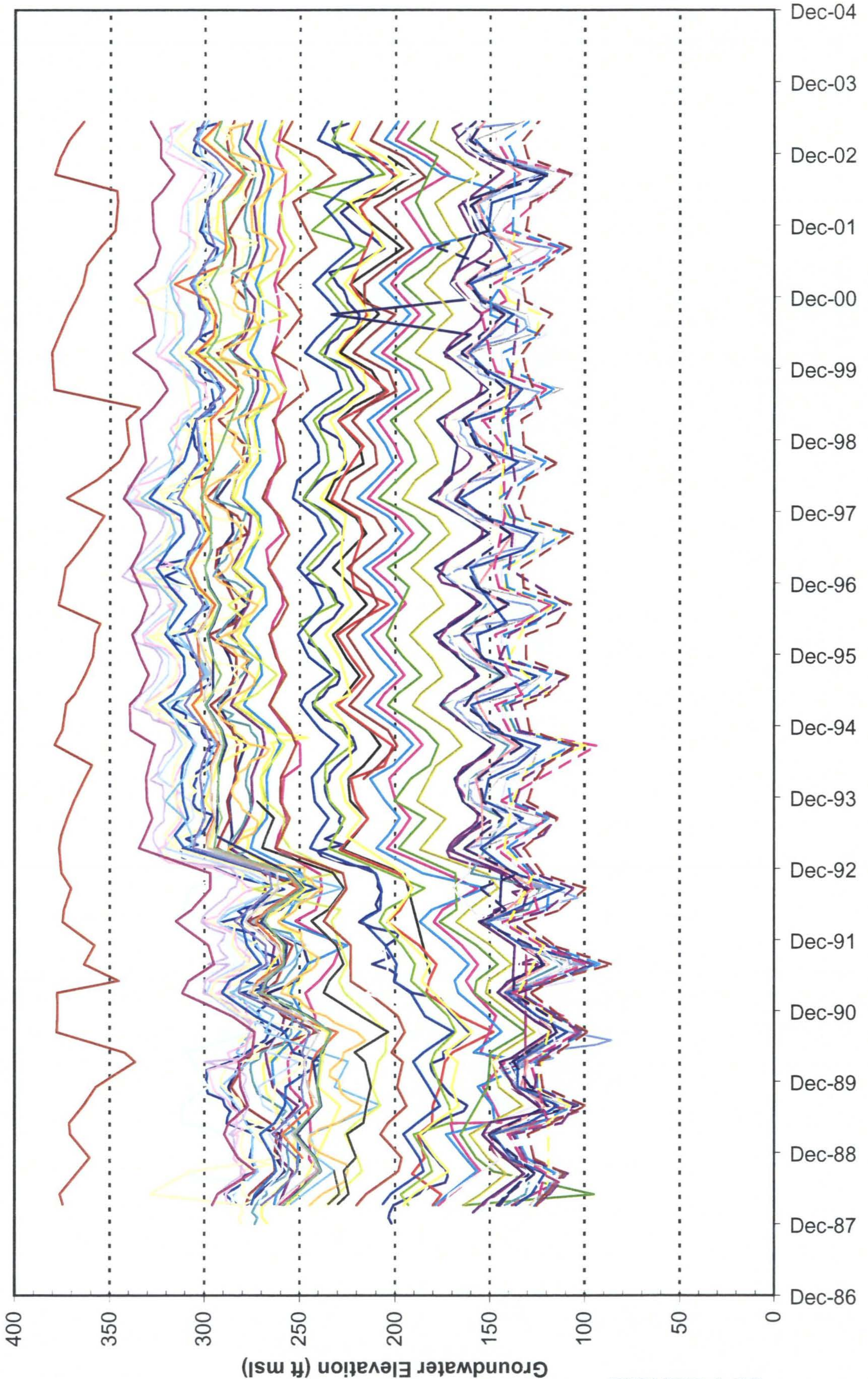


FIGURE 1-38
HYDROGRAPHS (ALL WELLS)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

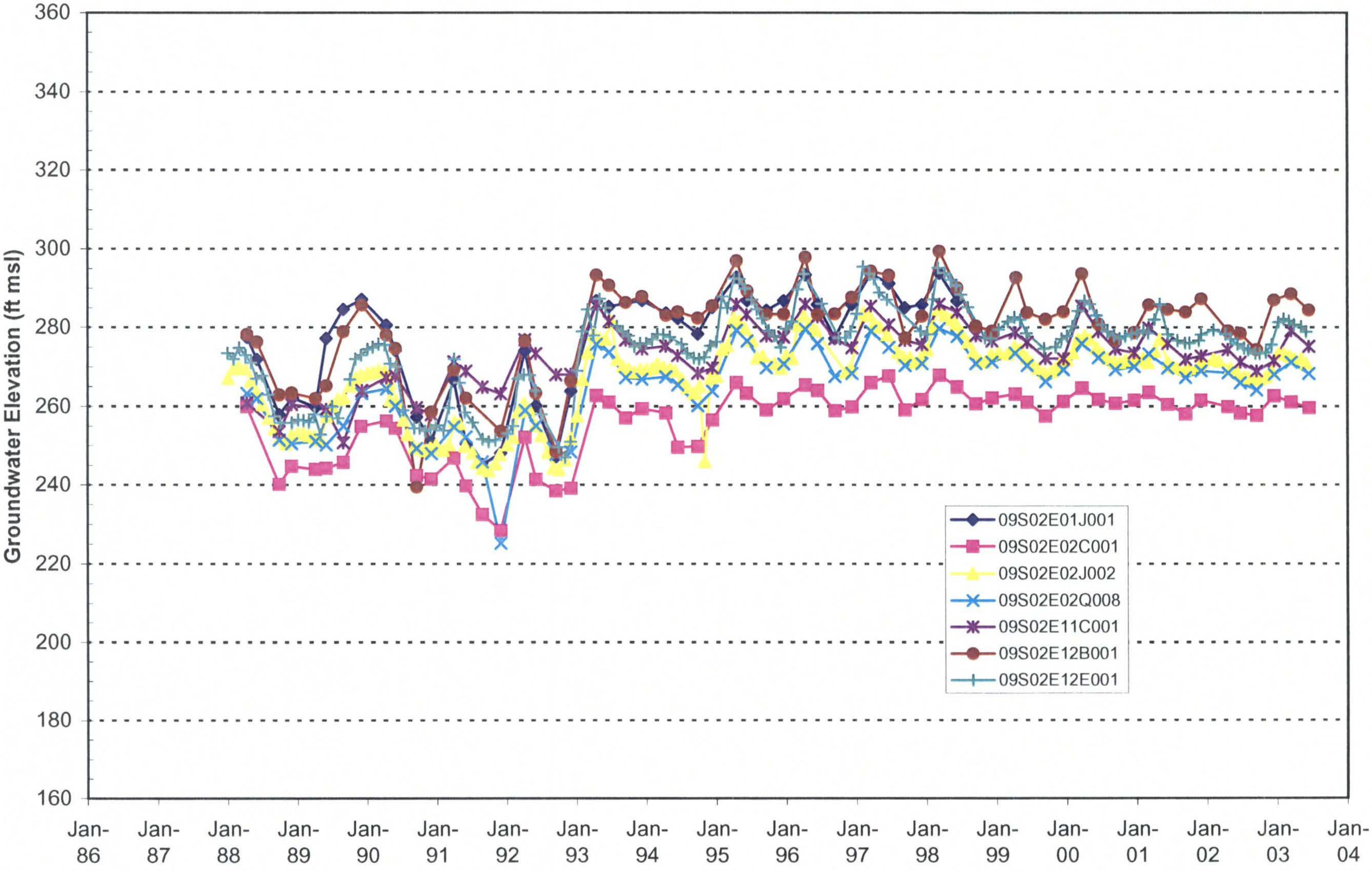


FIGURE 1-39
HYDROGRAPHS (09S02E)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

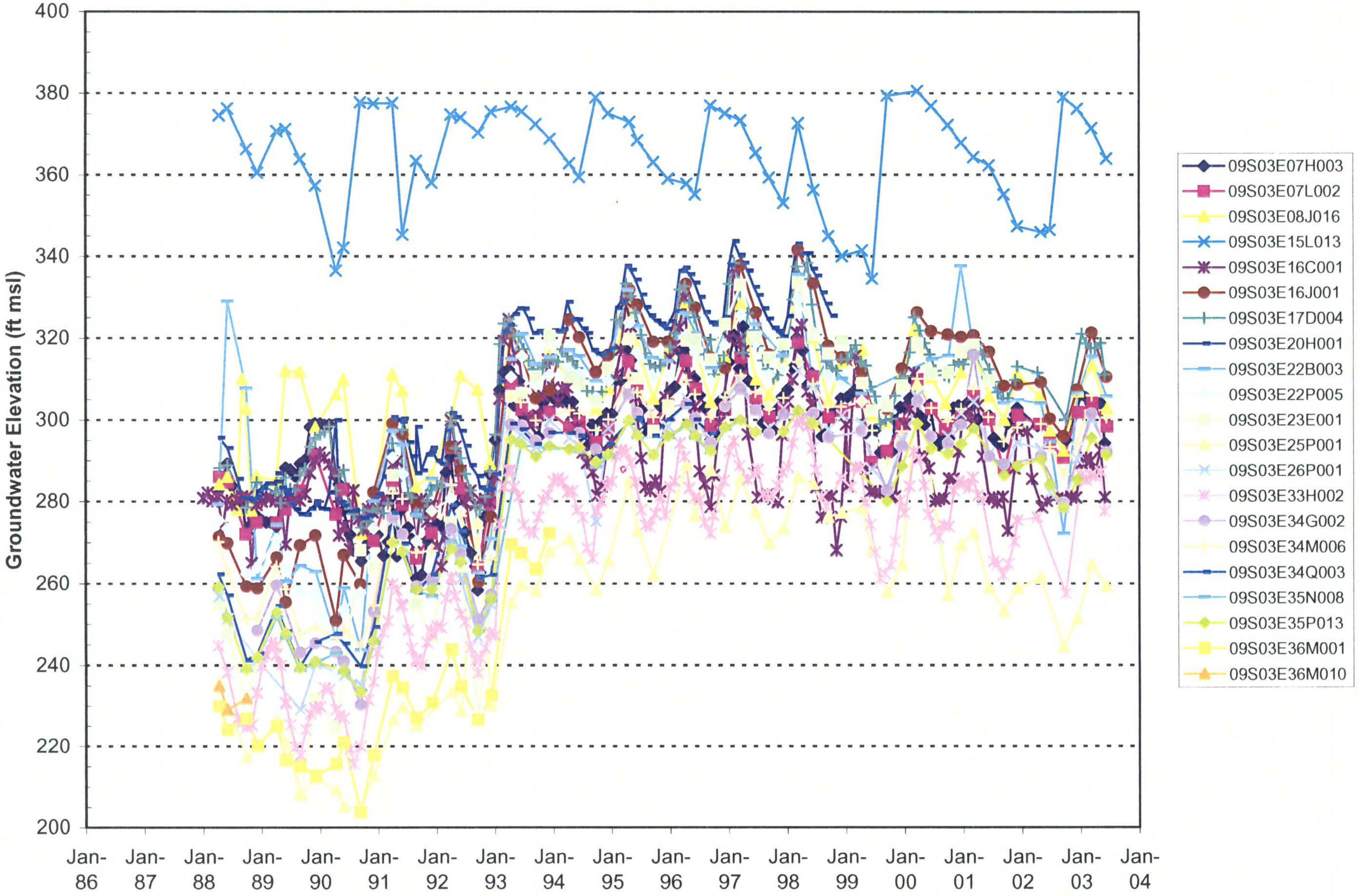


FIGURE 1-40
HYDROGRAPHS (09S03E)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 3-33_4/16/04_ccc_sfo

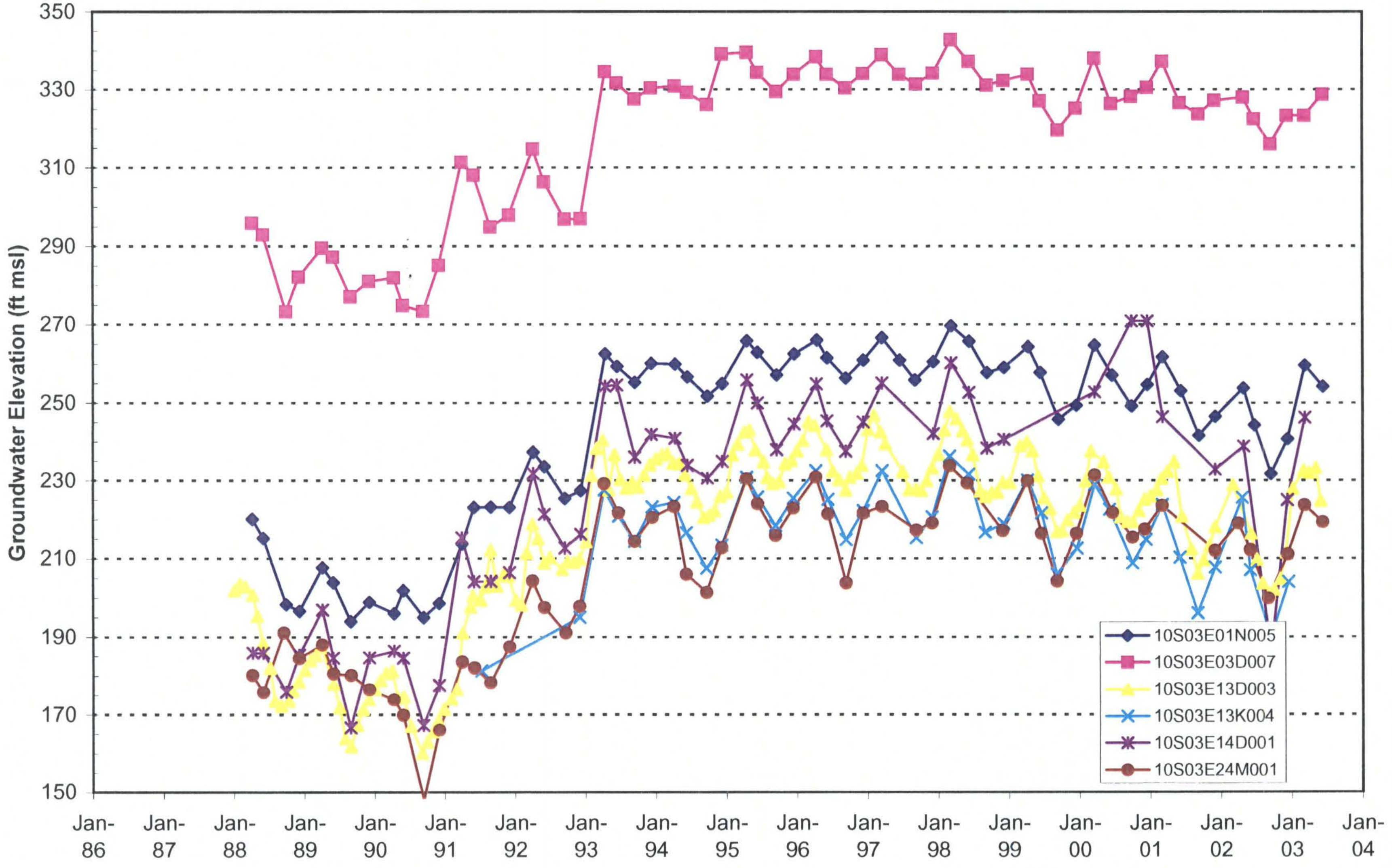


FIGURE 1-41
HYDROGRAPHS (10S03E)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

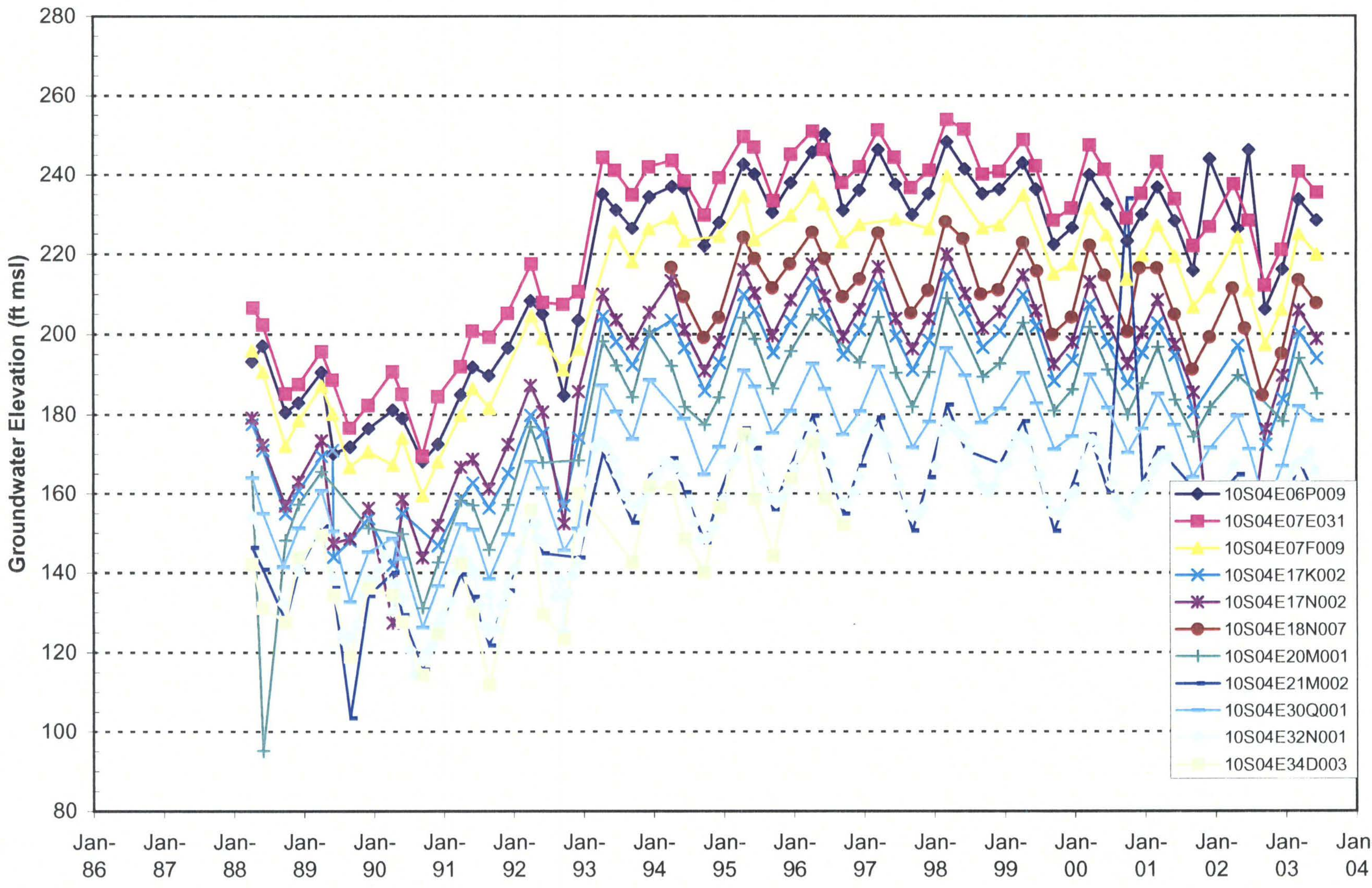


FIGURE 1-42
HYDROGRAPHS (10S04E)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

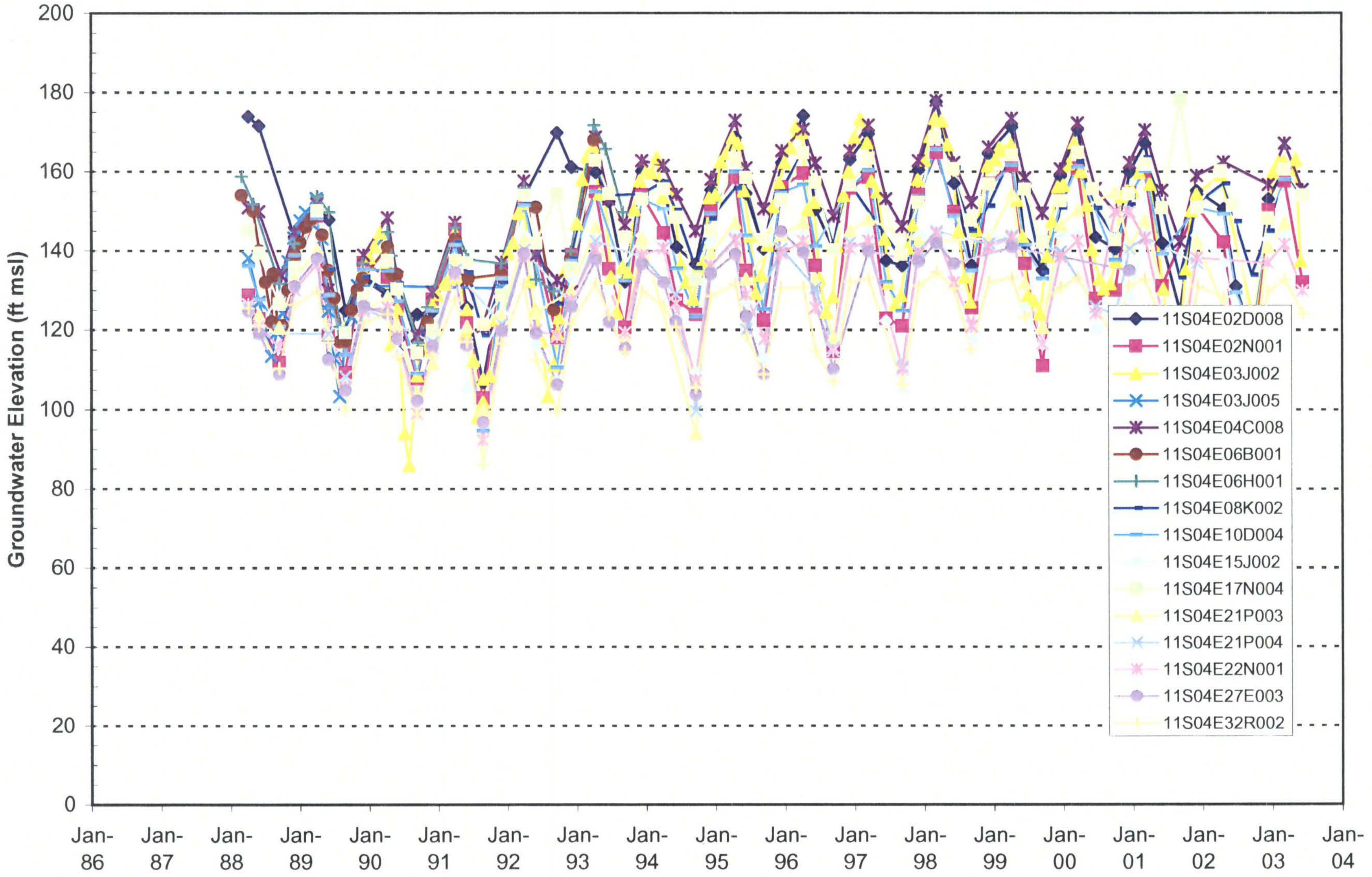
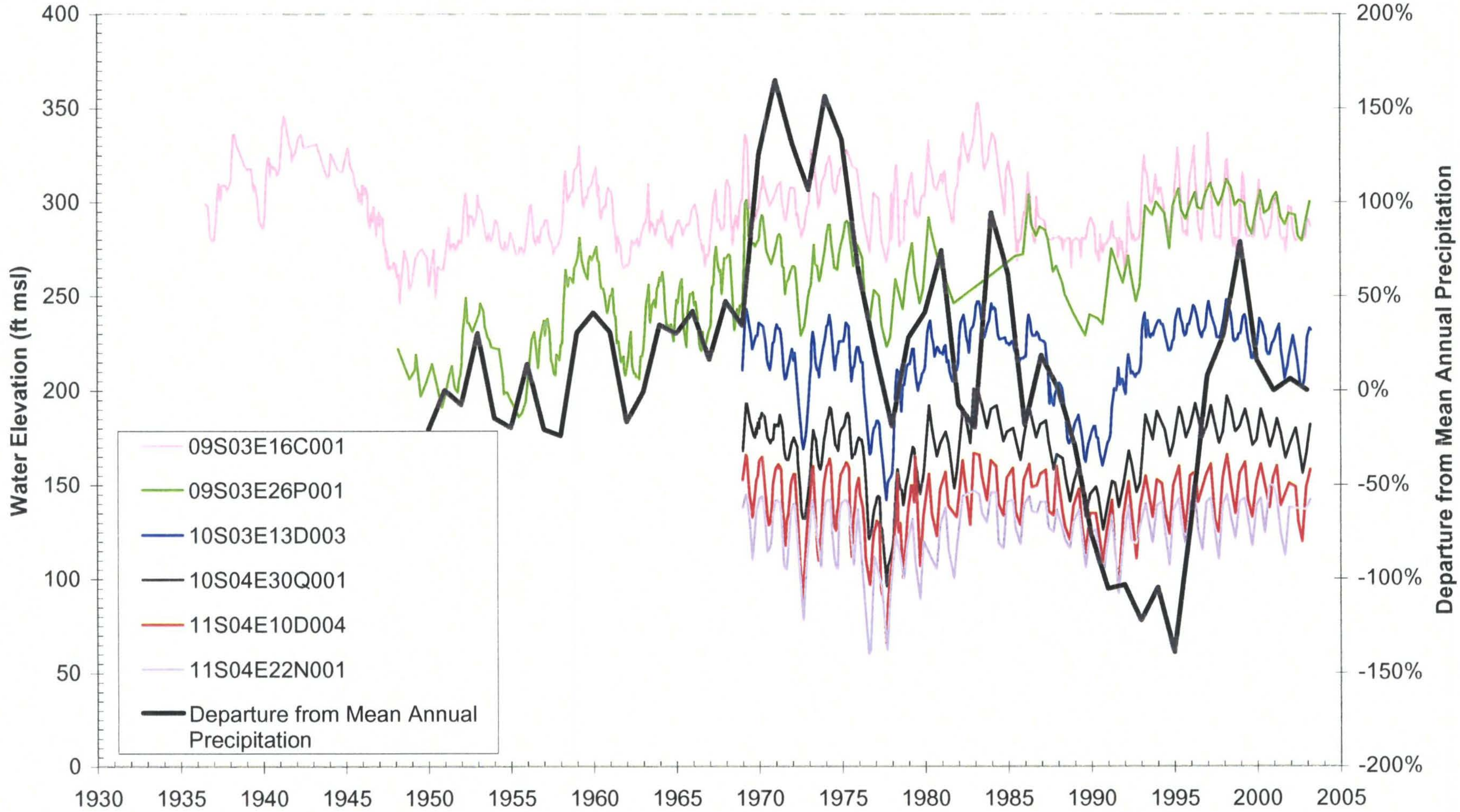


FIGURE 1-43
HYDROGRAPHS (11S04E)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Hydrographs.xls -- C_DWR_and_SCVWD -- 04/14/2004

FIGURE 1-44
LONG-TERM HYDROGRAPHS AND CLIMATIC TRENDS

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 3-37_4/16/04_ccc_sfo

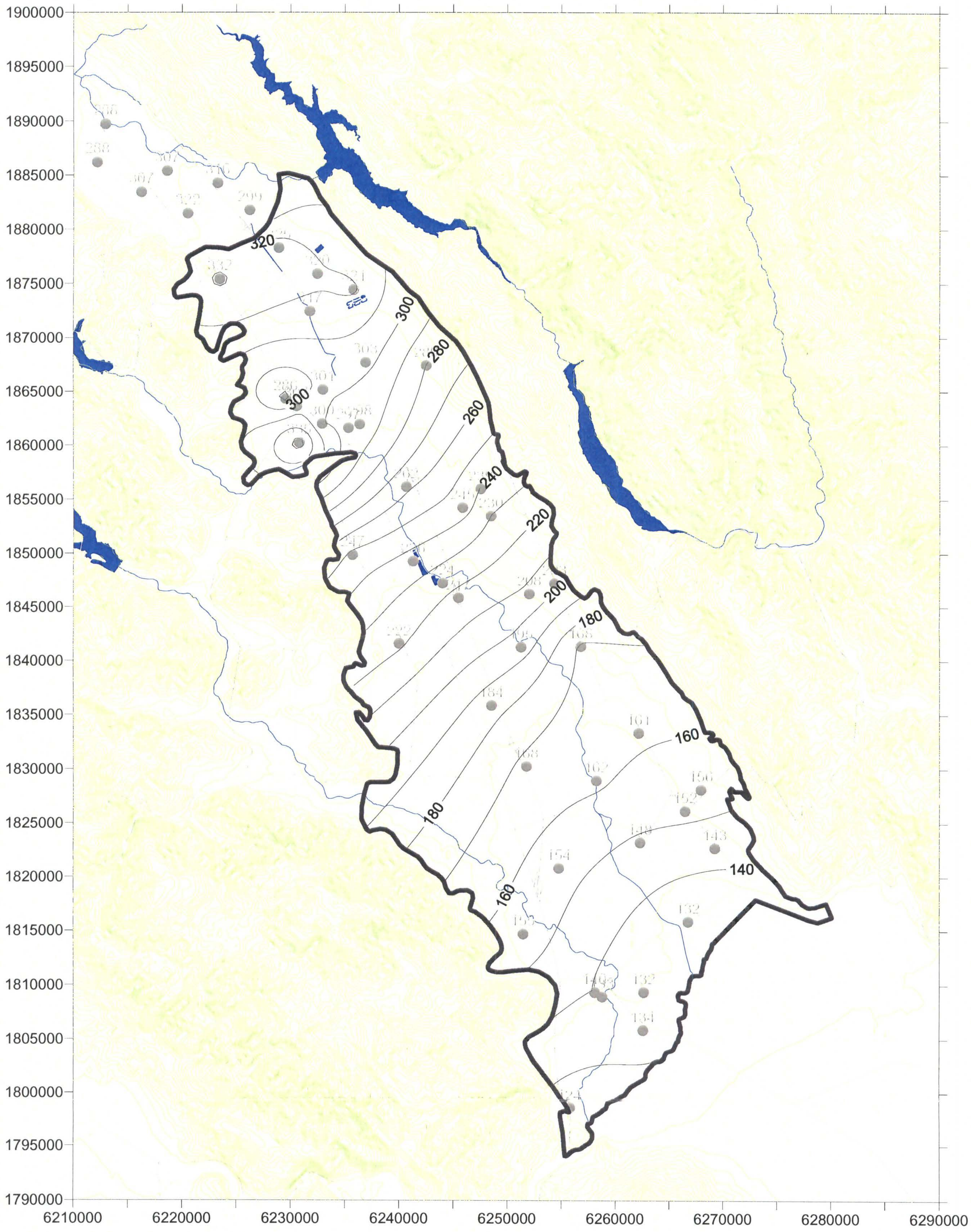


FIGURE 1-45
STEADY STATE WATER LEVELS (1996-98)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

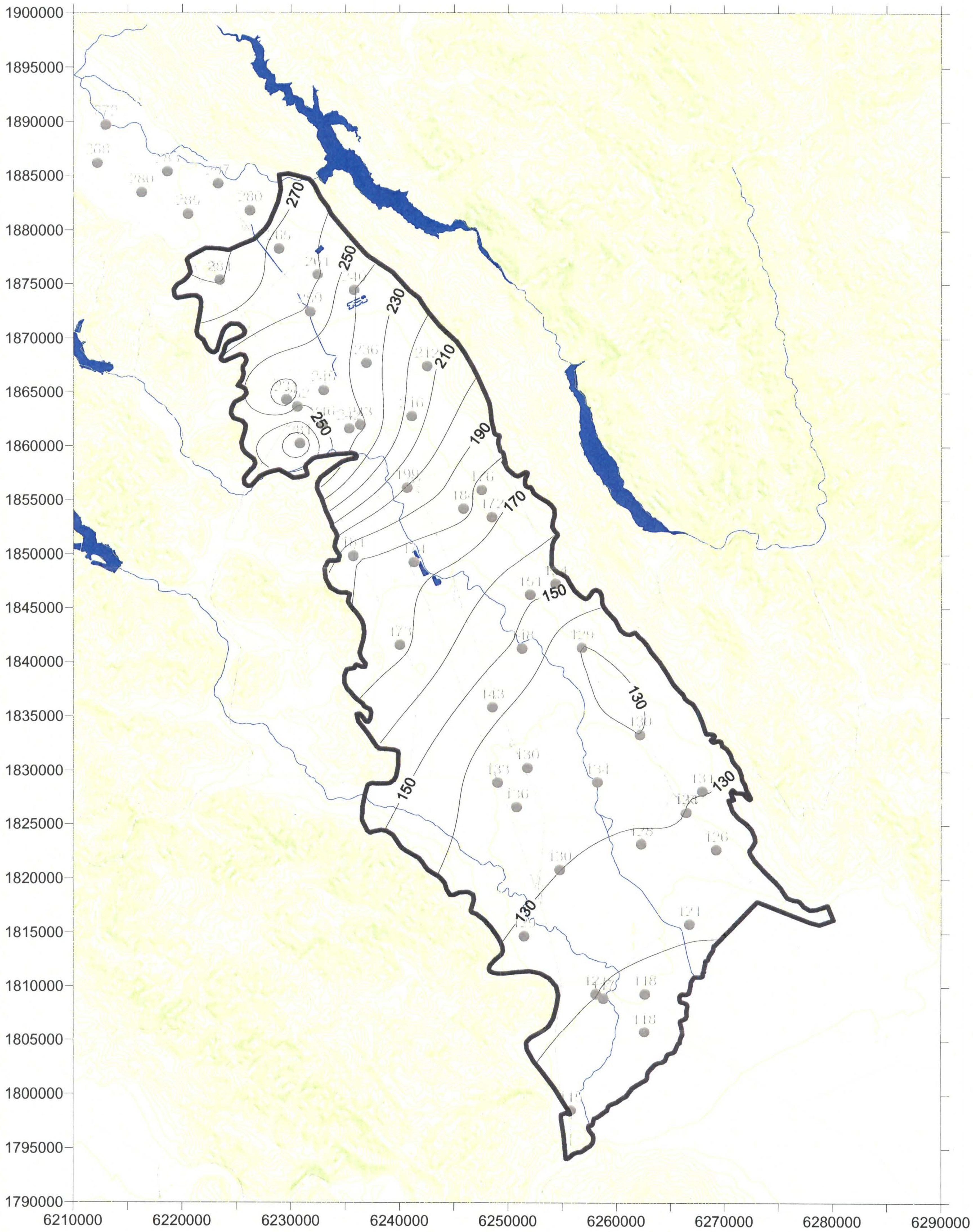


FIGURE 1-46
LOW WATER LEVELS (1989-90)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409.LB.05_Fig 3-39_4/16/04_ccc_sfo

CH2MHILL

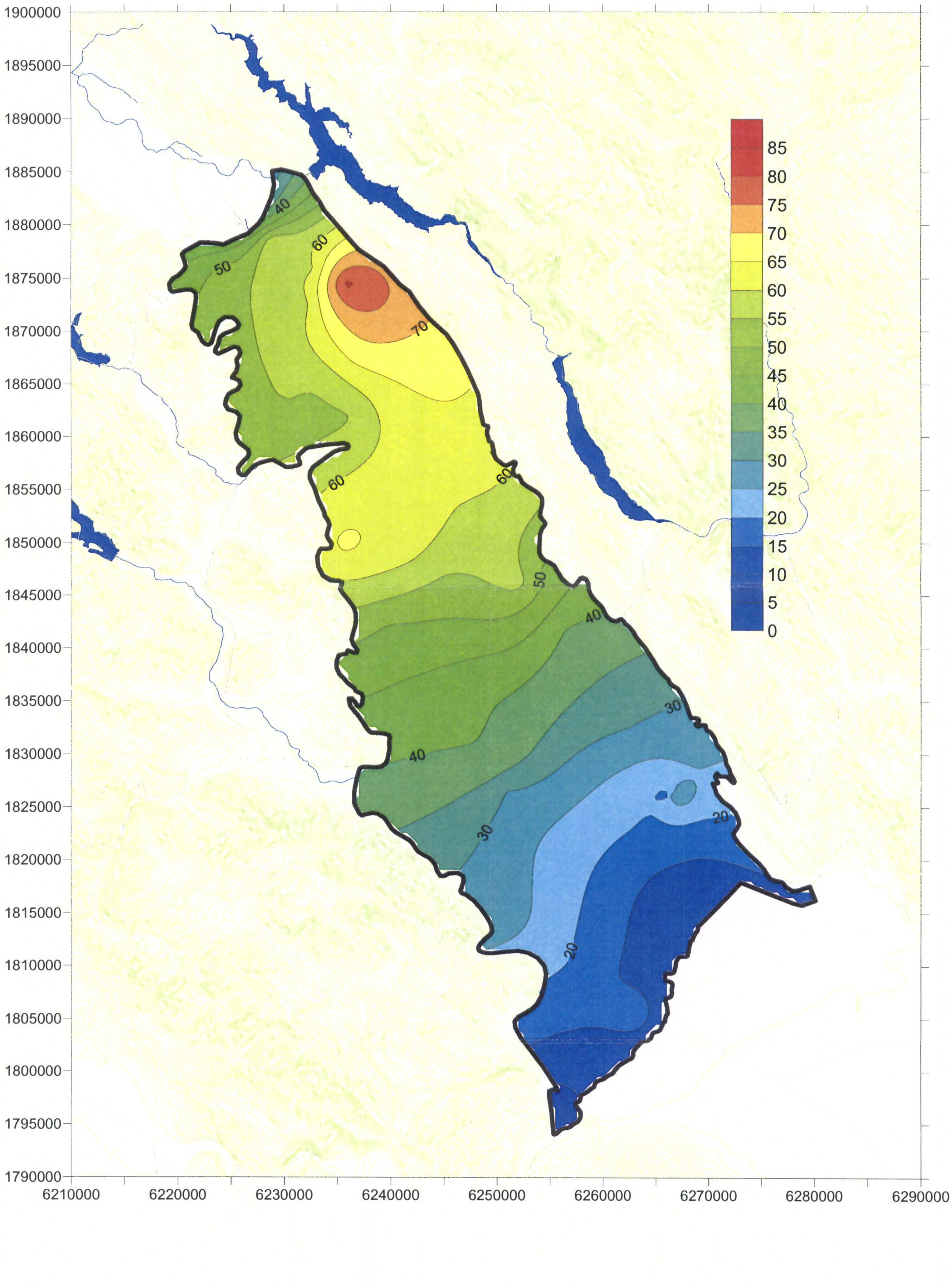
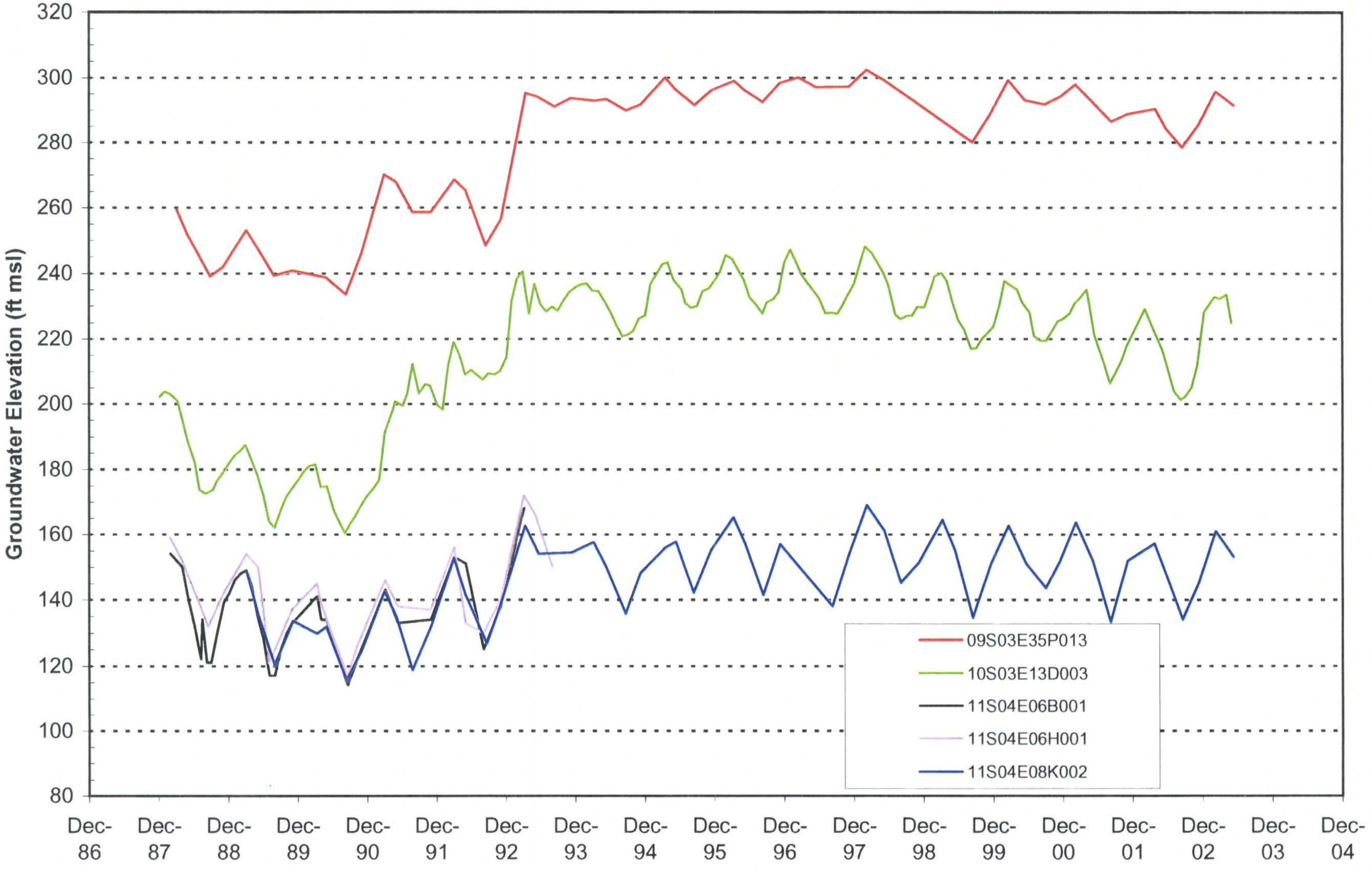


FIGURE 1-47
WATER LEVEL DIFFERENCE MAP (STEADY STATE - LOW)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

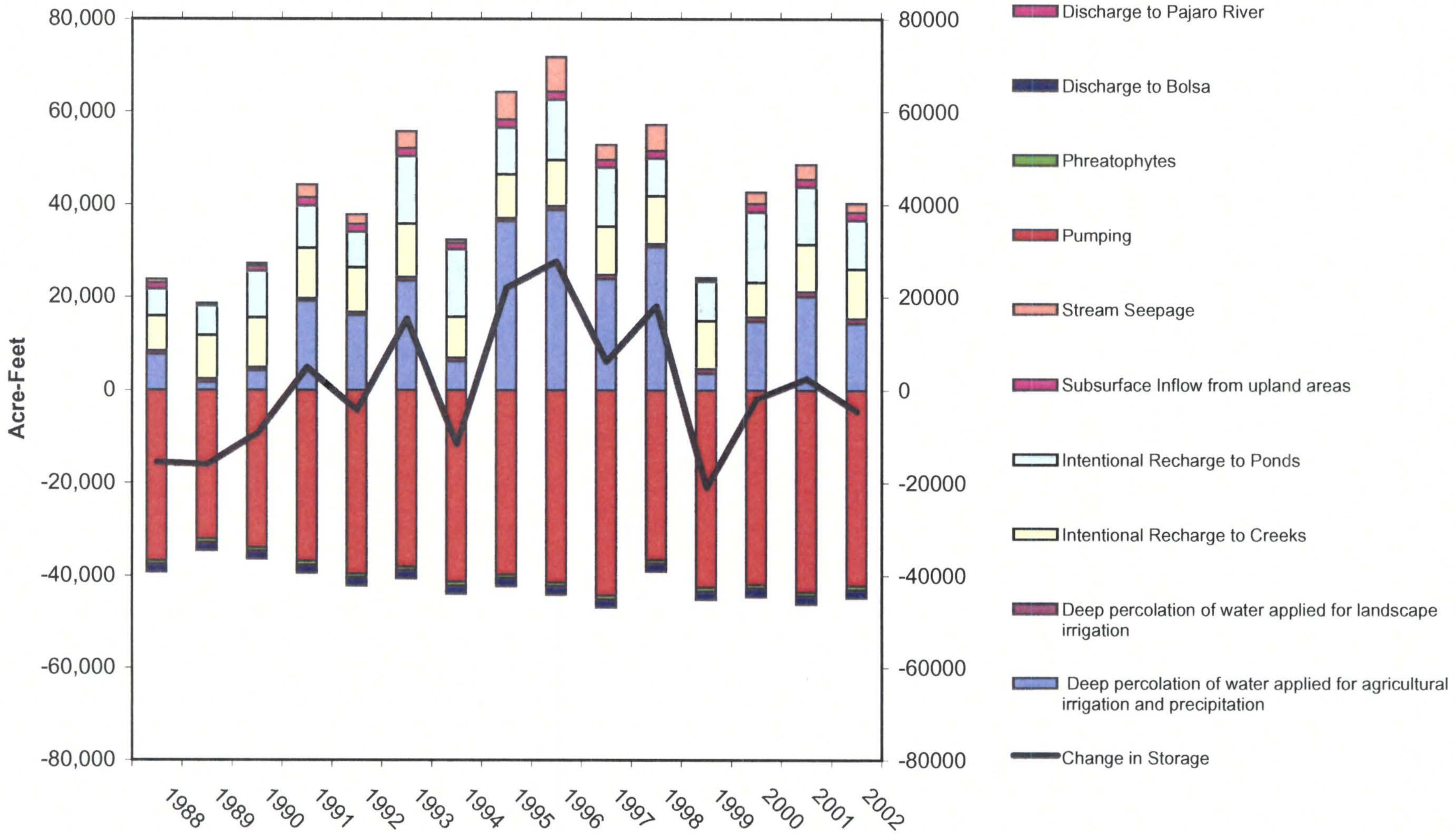


Hydrographs.xls -- C-ScrndWells

FIGURE 1-48
HYDROGRAPHS OF WELLS WITH SCREEN DATA

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Hydrographs.xls -- C-ScrndWells

FIGURE 1-49
WATER BUDGET SUMMARY
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

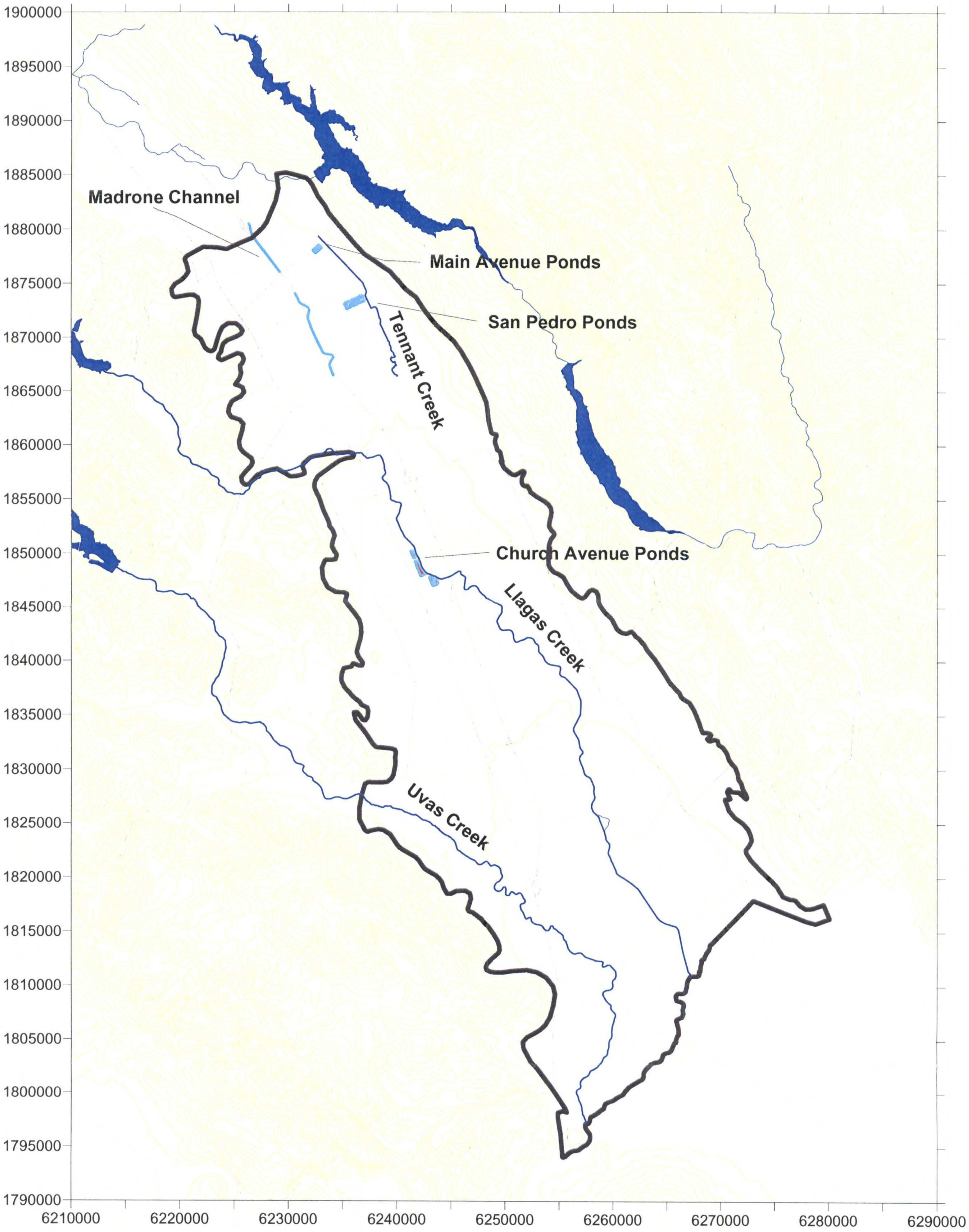
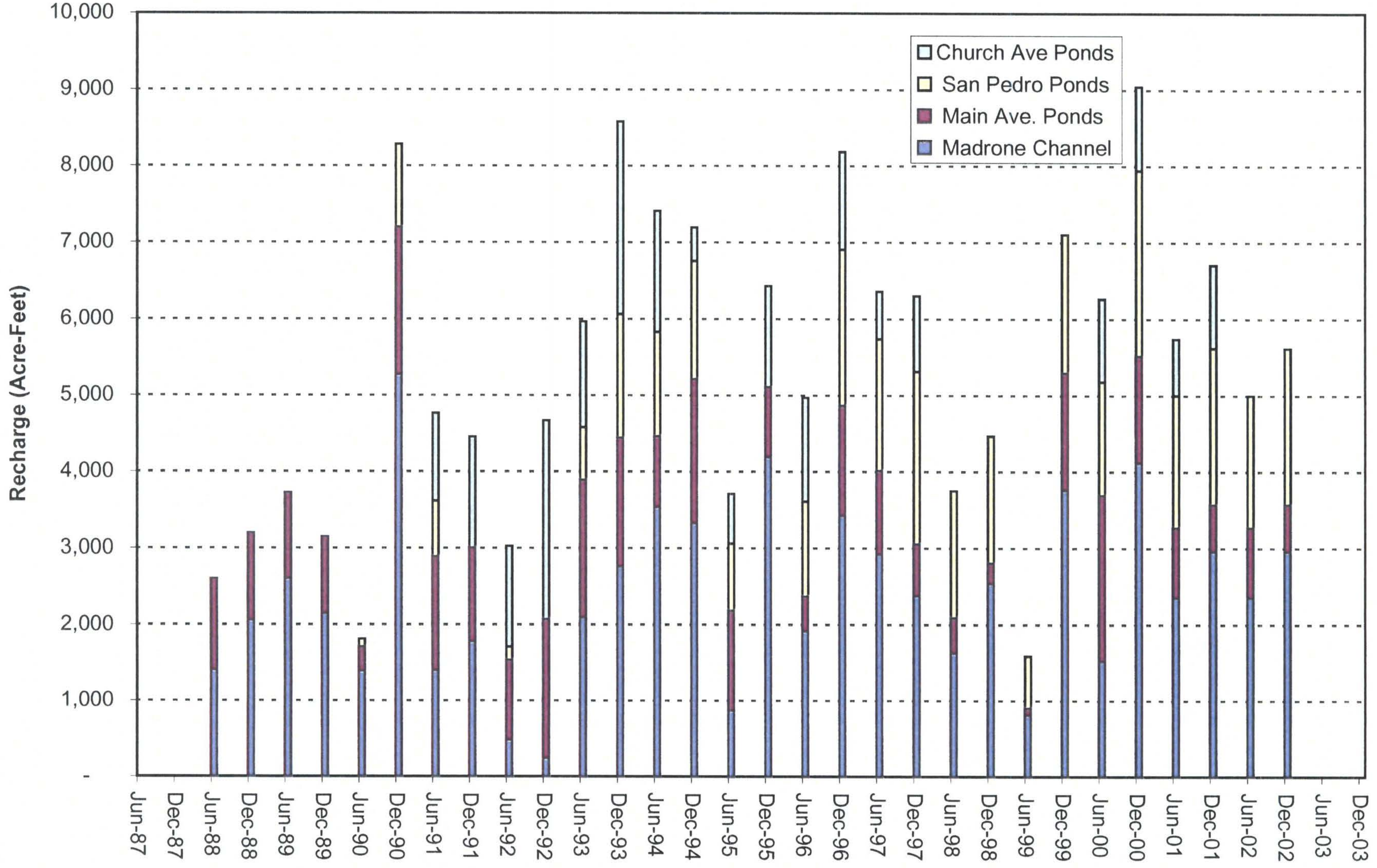


FIGURE 1-50
POND AND CREEK RECHARGE FACILITIES
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409.LB.05_Fig 4-2_4/16/04_ccc_sfo

CH2MHILL

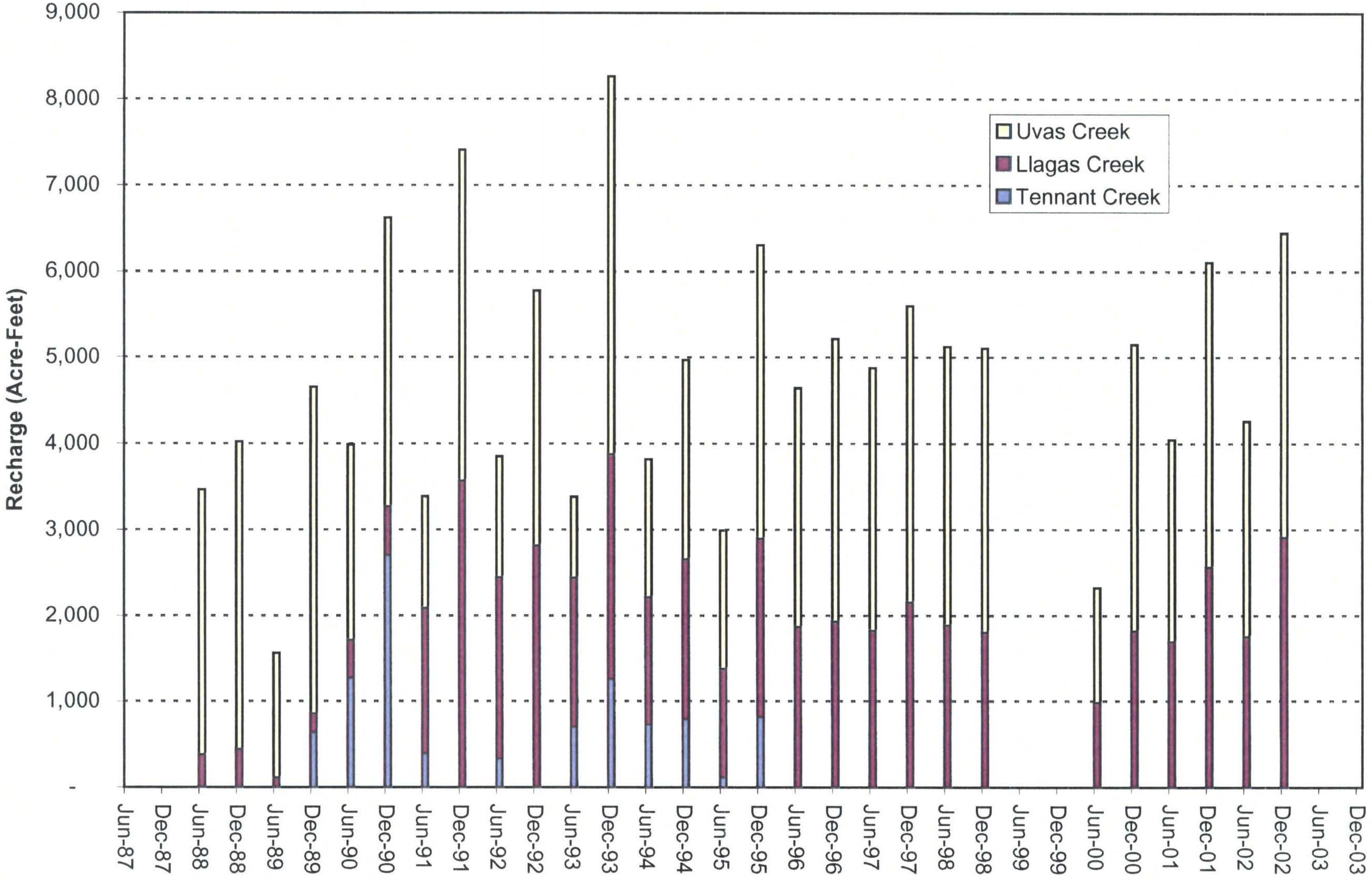


Hydrographs.xls -- C-ScrndWells

FIGURE 1-51
POND RECHARGE SUMMARY
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05 _Fig 4-3_4/16/04_ccc_sfo



Hydrographs.xls -- C-ScrndWells

FIGURE 1-52
STREAMBED RECHARGE SUMMARY
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

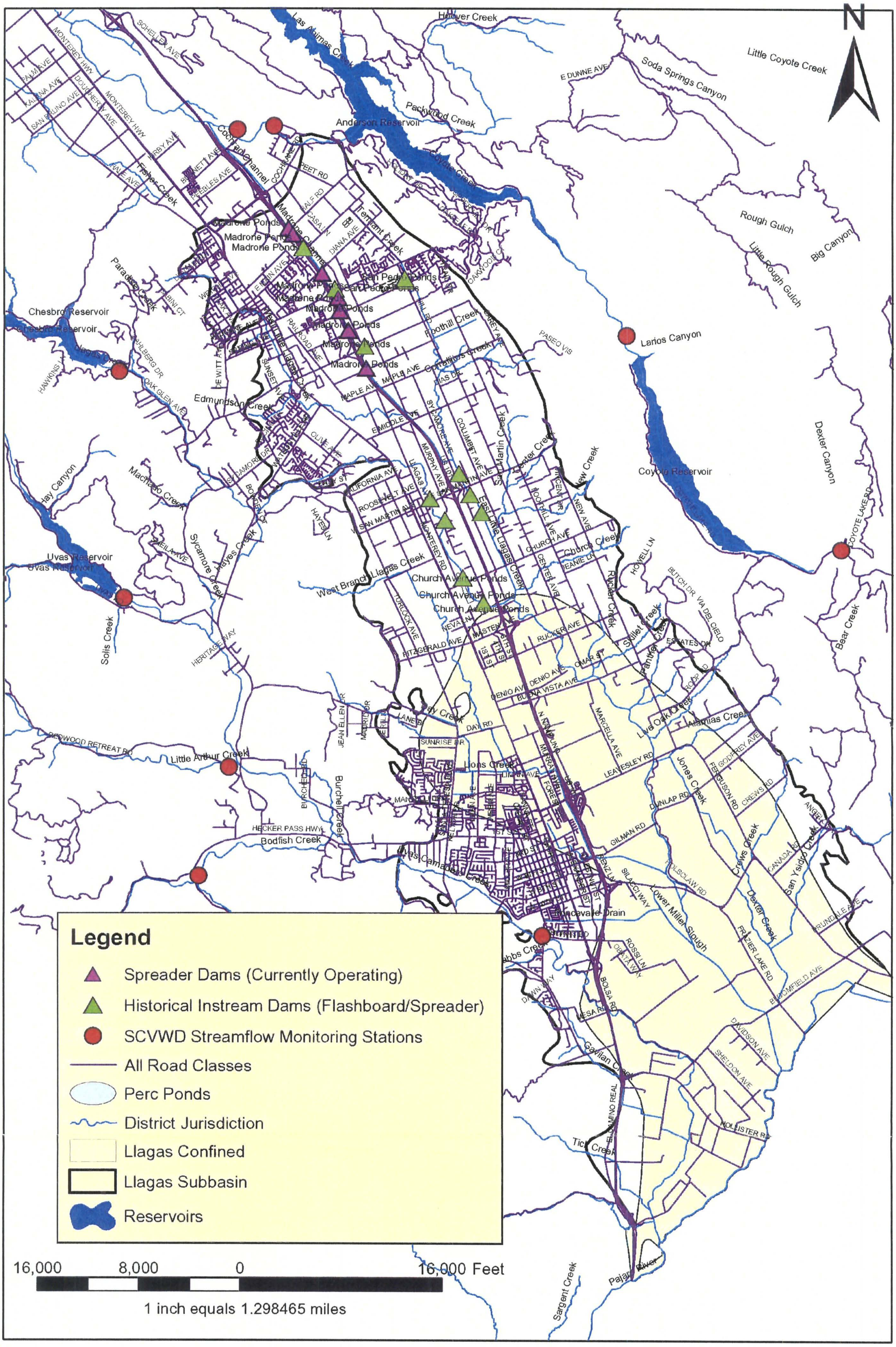


FIGURE 1-53
LOCATION OF SPREADER DAMS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

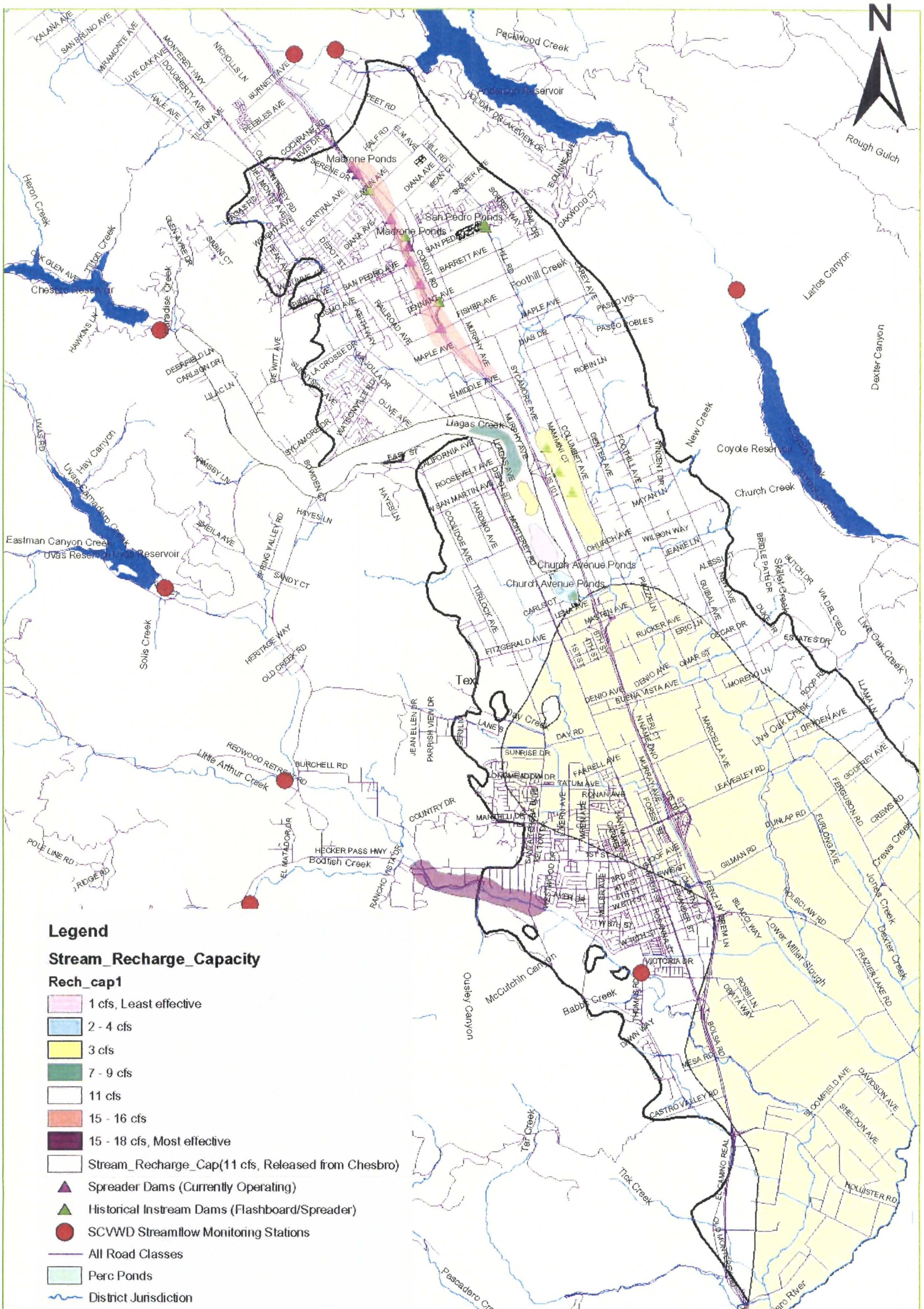
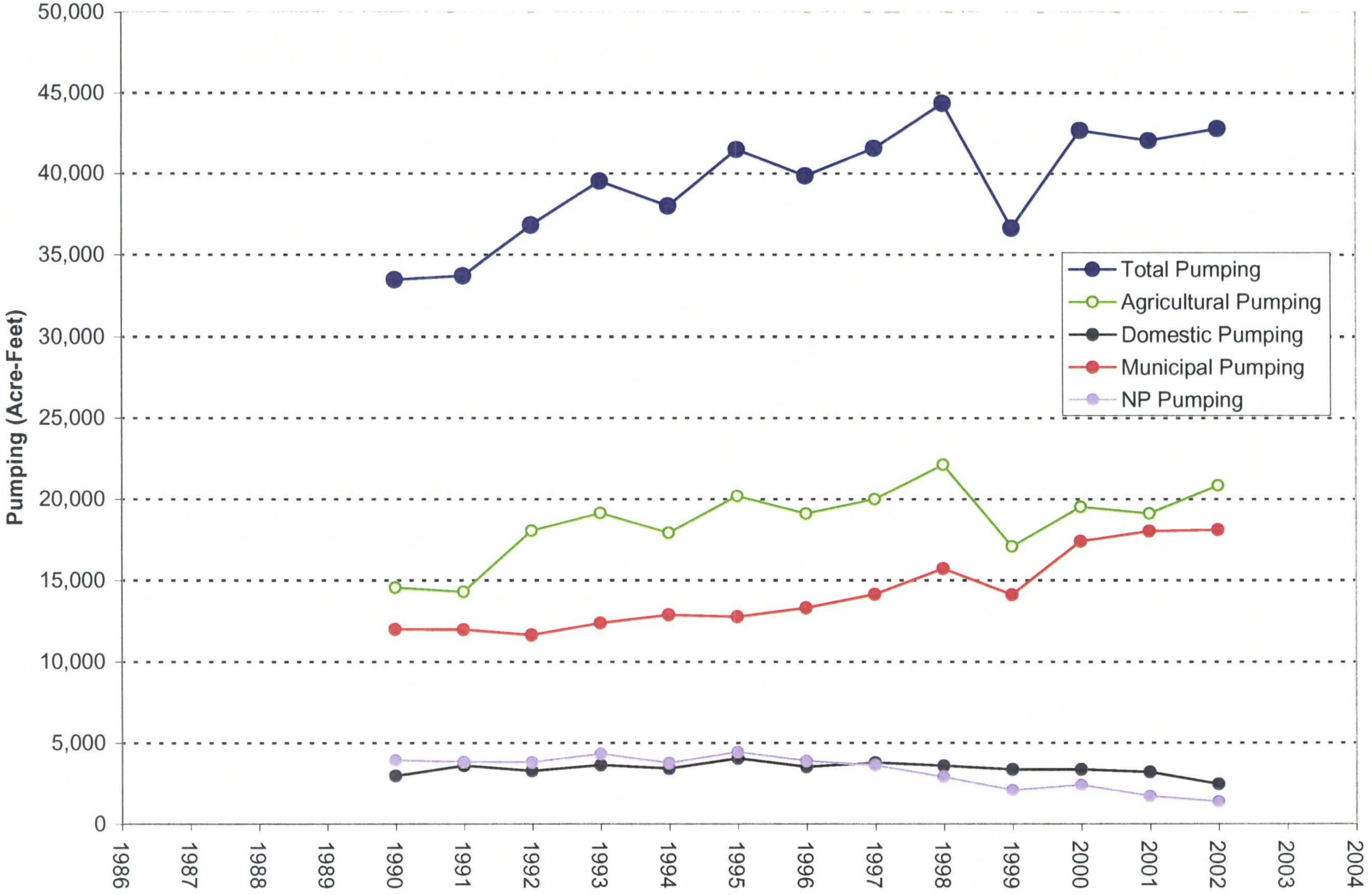


FIGURE 1-54
LOCATION OF STREAMBED RECHARGE CAPACITIES
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT



Hydrographs.xls -- C-ScrndWells

FIGURE 1-55
PUMPING SUMMARY
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

SECTION 2

2.0 Numerical Model Development

2.1 Introduction

This section describes the numerical framework of the model. Modeling is being performed using the MODFLOW-2000 (CH2M HILL, 2000) code to simulate groundwater flow in the basin under specified stresses. A 15-year period beginning in water-year 1988 and terminating at the end of water-year 2002 is used for transient calibration. Stress periods are based on water-year semesters. For example: water-year 1988 consists of two stress periods, the first beginning October 1, 1987 and ending March 31, 1988. The second stress period begins April 1, 1988 and ends September 30, 1988.

2.2 Model Grid

The boundaries of the model grid encompass the main alluvial areas of Llagas Valley (see Figure 1-1 and Section 1.2.1. The model contains four active layers of uniform 500-foot squares in the X and Y directions corresponding to 122,000 model cells, of which 26,049 are active (Figure 2-1). Model rows and columns align with those of the Coyote Basin Groundwater Model (CH2M HILL 2000).

Results of the conceptual model review indicate an absence of basin-wide hydrostratigraphic layering; accordingly, for modeling purposes, the basin was subdivided into parallel layers that roughly coincide with distribution of production-well perforations. Figures 2-2 to 2-5 illustrate the average incidence of production-well perforations with depth for four well groups based on their locations within the basin. Based on the average low water level for the period 1988 to 2002, zones with a high incidence of perforations, and depth to bedrock, the basin was vertically discretized into four layers. Figures 2-6 to 2-8 illustrate the model layers in select cross sections along the principal axis of the basin. A complete set of cross sections for the basin is presented in Figures 1-10 through 1-31. The top of Layer-1 coincides with land surface. The bottom of Layer-1 is below the lowest water levels anticipated during simulations and the bottom of Layer-4 is bedrock interpreted from cross sections.

2.3 Hydrogeologic Properties

Several methods were used to initially (prior to calibration) distribute aquifer properties in the basin. They are using pumping test and specific capacity data for wells in the basin and the borehole lithology method. As discussed in the following section, calibration was attempted for each. The borehole lithology method was attempted first and is presented below. As discussed in Section 1.3.2, Hydrostratigraphic Units, lithologies presented on DWR driller logs were placed into one of 11 categories based on the USCS. Five layers were defined (four model layers for the alluvium and one additional layer representing bedrock) that were used for numerical modeling purposes. The lithologic categories were lumped into four groups: 1) gravel/sand, 2) sand, 3) silt/sand (assumed 50/50), and 4) clay. The relative percentage of each of these four lithologies within each of the model layers was calculated for each well. These percentages were then used to interpolate values to the center of each cell where no log data were available. A kriging routine was used for the interpolation.

The interpolated values of the percentage of gravel/sand, sand, silt/sand, and clay form the initial basis for changing aquifer properties within the model. Values of hydraulic conductivity (K) are automatically assigned to each of the grid cells based upon: 1) a user-defined estimate of these properties for each of the four alluvial units; and 2) the interpolated percentages of each of the units. An anisotropy factor was also included along the axis of the valley to reflect depositional trends consistent with an alluvial environment. Hydraulic conductivity therefore represents a weighted average. Examples of interpolated hydraulic conductivity fields for each model layer are presented in Figures 2-9 to 2-12. Hydraulic conductivity fields interpolated by this method are intended to be a "first cut" attempt to adhere to the geologic information available in logs. As discussed in the next section, the method of initially distributing aquifer properties and hydraulic conductivity values themselves change during the calibration process.

Specific yield in Layer-1 and specific storage in Layer-2 through Layer-3 will be evaluated. Initial values of specific yield and specific storage are 10 percent and 2E-6, respectively.

2.4 Steady-state and Initial Conditions

Hydrographs for wells in the basin indicate that a period of relatively steady water levels existed from 1996 to 1998. Using this time period as a basis, average water levels were calculated and used to create a water level map. Initial conditions for the steady-state flow model are based on head distributions presented in Figure 2-13. As discussed in the following section, a true steady-state period could not be simulated for calibration because climatic conditions during the period of calibration transitioned from one extreme to another and the basin was essentially full for the period 1996 to 1998.

Transient model simulation begins at water year 1988 (October 1987) and terminates at the end of water year 2002 (September 2002). An initial head distribution for the transient simulations is based on the average water levels for water year 1988. A plot of head distributions used for initial heads during transient simulation is presented in Figure 2-14.

2.5 Model Fluxes and Boundaries

The model contains numerous flux parameters, including: deep percolation of precipitation and water applied for irrigation, intentional recharge to creeks and ponds, subsurface inflow from bedrock uplands and alluvial tributary canyons, stream seepage, and agricultural, domestic, and municipal pumping. Fluxes within the model are based on a 15-year period of water budget components developed in the draft conceptual model. Fluxes in and out of the model are simulated using various boundary conditions.

2.5.1 Deep Percolation of Precipitation and Water Applied for Agricultural Irrigation

Deep percolation of precipitation and water applied for agricultural irrigation were estimated on a monthly basis utilizing soil moisture budget modeling and represented in the model as areal recharge using the MODFLOW Recharge Package. Spatial variability and magnitude of the recharge change for each stress period depending on land use, rainfall, and agricultural pumping during that period.

2.5.2 Intentional Recharge to Creeks and Ponds

The District operates a number of artificial recharge facilities in the northern portion of the Llagas Basin. Controlled recharge to these facilities is a major component of groundwater recharge to the Llagas Basin. Creek and pond recharge data for the period 1988 to 2002 were provided by the District and are represented in the model as a specified flux. Based on the location of the recharge provided by the District, intentional recharge was applied using injection wells in model Layer-1 (Figure 2-15; also see Figures 1-50, 1-53, and 1-54.

2.5.3 Subsurface Inflow from Bedrock Uplands and Alluvial Tributary Canyons

Subsurface inflow from fractured bedrock provides recharge to the basin along mountain front areas. In addition, subsurface inflow occurs from alluvial tributary canyons (e.g., Uvas and Llagas Creeks). Estimates of subsurface inflow from fractured bedrock along mountain front areas and inflow from alluvial canyons were made on an annual basis for the years 1988 to 2002. Estimated inflow is represented in the model as a specified flux along the eastern and western model boundaries using injection wells (Figure 2-16). Injection wells used to simulate subsurface inflow are located in model cells directly adjacent to the no-flow boundary and are screened in the lowermost active layers.

2.5.4 Pajaro River

Groundwater-surface water interactions along the Pajaro River are simulated as a head-dependent condition using the MODFLOW River Package (Figure 2-17). Stage data from the Chittenden gage (station #11159000), located southwest of the study area, are used as a surrogate for simulating seasonal river stage fluctuations.

2.5.5 Stream Seepage

Stream seepage from creeks, including Llagas and Uvas, is simulated using a specified flux along mountain front areas (Figure 2-17). This specified flux was represented in the model as injection wells.

2.5.6 Lateral Boundaries

A groundwater divide separates the Llagas and Coyote Basins and was set as a no-flow boundary. This groundwater divide fluctuates seasonally but is generally centered on the Cochran Road area.

The southern boundary of the model was placed in the Bolsa Basin. Flow in and out of this basin is subject to variation based on conditions outside of and within the basins (i.e., driven by water level variations). Groundwater may flow into or out of Llagas Basin depending on water levels. This boundary is simulated with a head-dependent boundary (Figure 2-18). Numerically, flux across this boundary is dependent on simulated changes in head within the aquifer adjacent to the boundary. In this case, the boundary with Bolsa Basin is simulated two miles south of the Pajaro River. The general head boundary was applied in layers 1 through 4.

2.5.7 Pumping

The primary source of discharge from the Llagas Basin is groundwater pumpage for M&I, agricultural, and domestic use. Pumping rates and locations were provided by the District based on the District groundwater extraction database (Figure 2-19). The District collects a user fee based on the number of acre-feet pumped during 6-month billing periods (January to June, and July to December). For incorporation into the model, these 6-month pumpage values were re-apportioned to water-year semesters based on monthly agricultural demand estimates (Table 2-1). The majority of pumping in the model is from Layer-2 and Layer-3.

TABLE 2-1
Fraction of Annual Pumping Based on Agricultural Demand Estimates

Month	Fraction of Total Annual Municipal Pumping	Fraction of Total Annual Agricultural Pumping
Oct	0.071	0.093
Nov	0.071	0.000
Dec	0.071	0.000
Jan	0.071	0.000
Feb	0.071	0.000
Mar	0.071	0.081
Apr	0.082	0.105
May	0.102	0.140
Jun	0.102	0.152
Jul	0.102	0.164
Aug	0.102	0.147
Sept	0.082	0.118

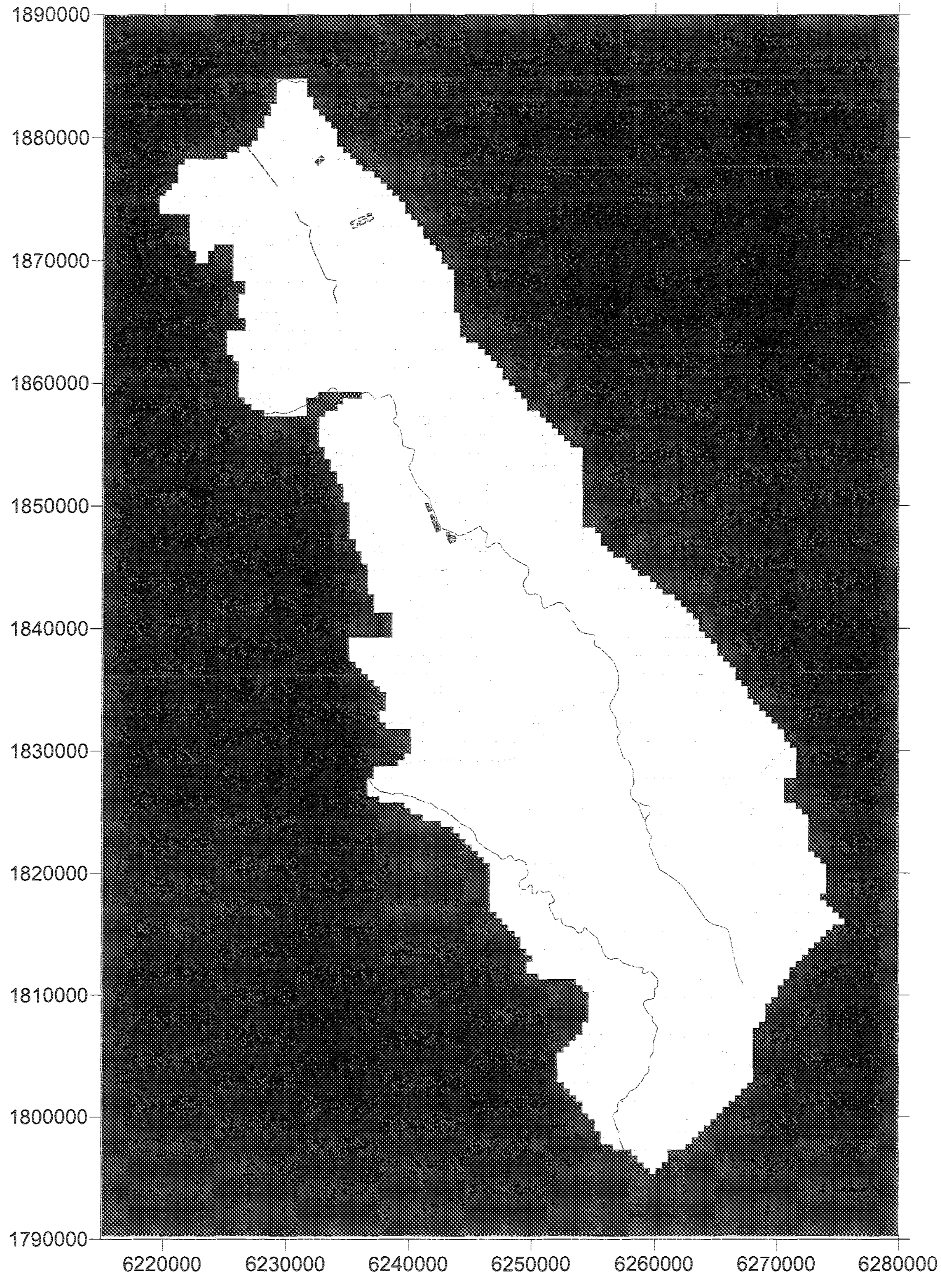
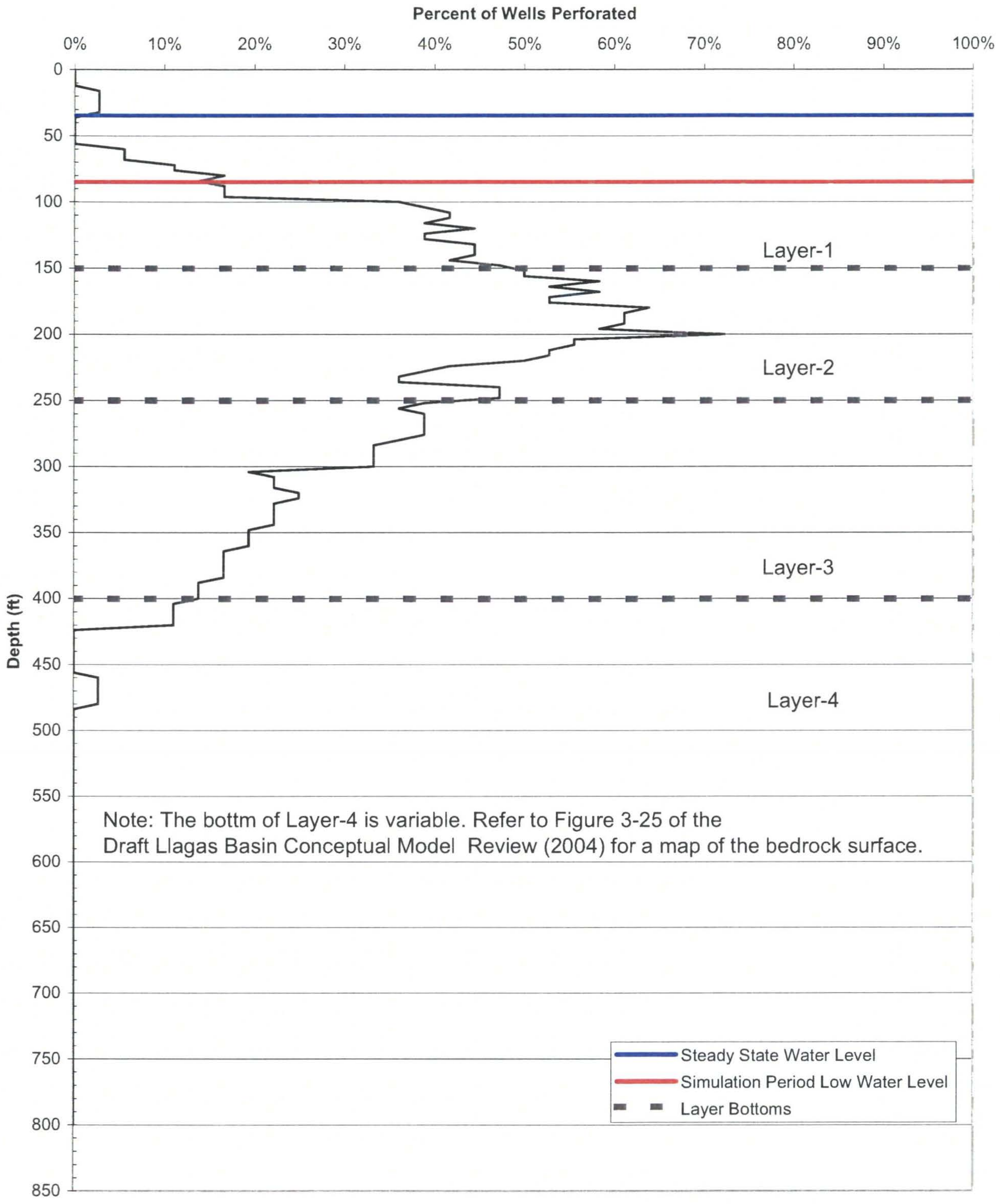


FIGURE 2-1
MODEL GRID (500 X 500)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



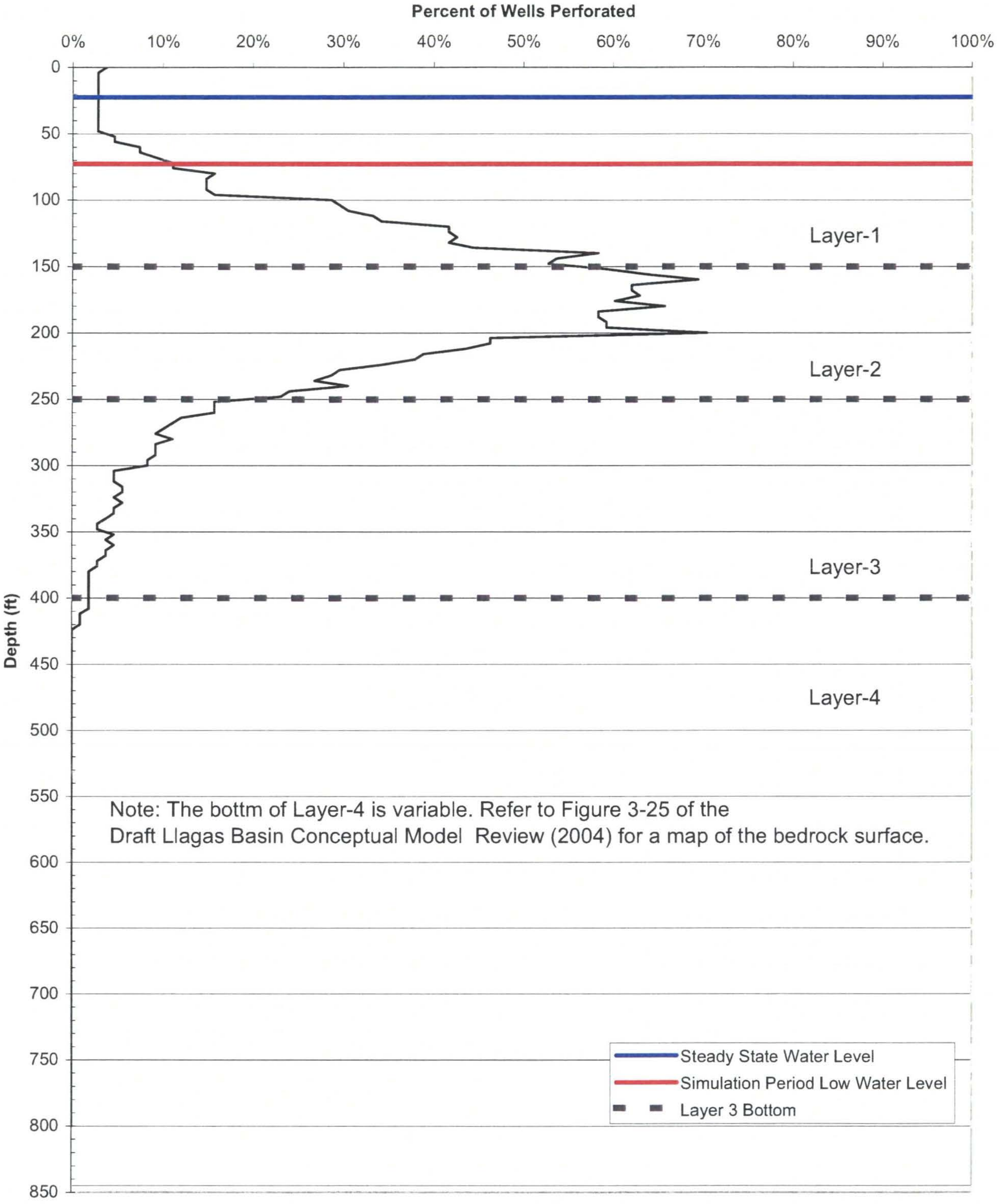
Note: The bottm of Layer-4 is variable. Refer to Figure 3-25 of the Draft Llagas Basin Conceptual Model Review (2004) for a map of the bedrock surface.

FIGURE 2-2
PRODUCTION WELL PERFORATIONS WITH DEPTH
09S03E WELLS (36 WELLS)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Screen_Frequency_Plots.xls -- C-PercentWells_09S03E (3) -- 06/17/2004

CH2MHILL

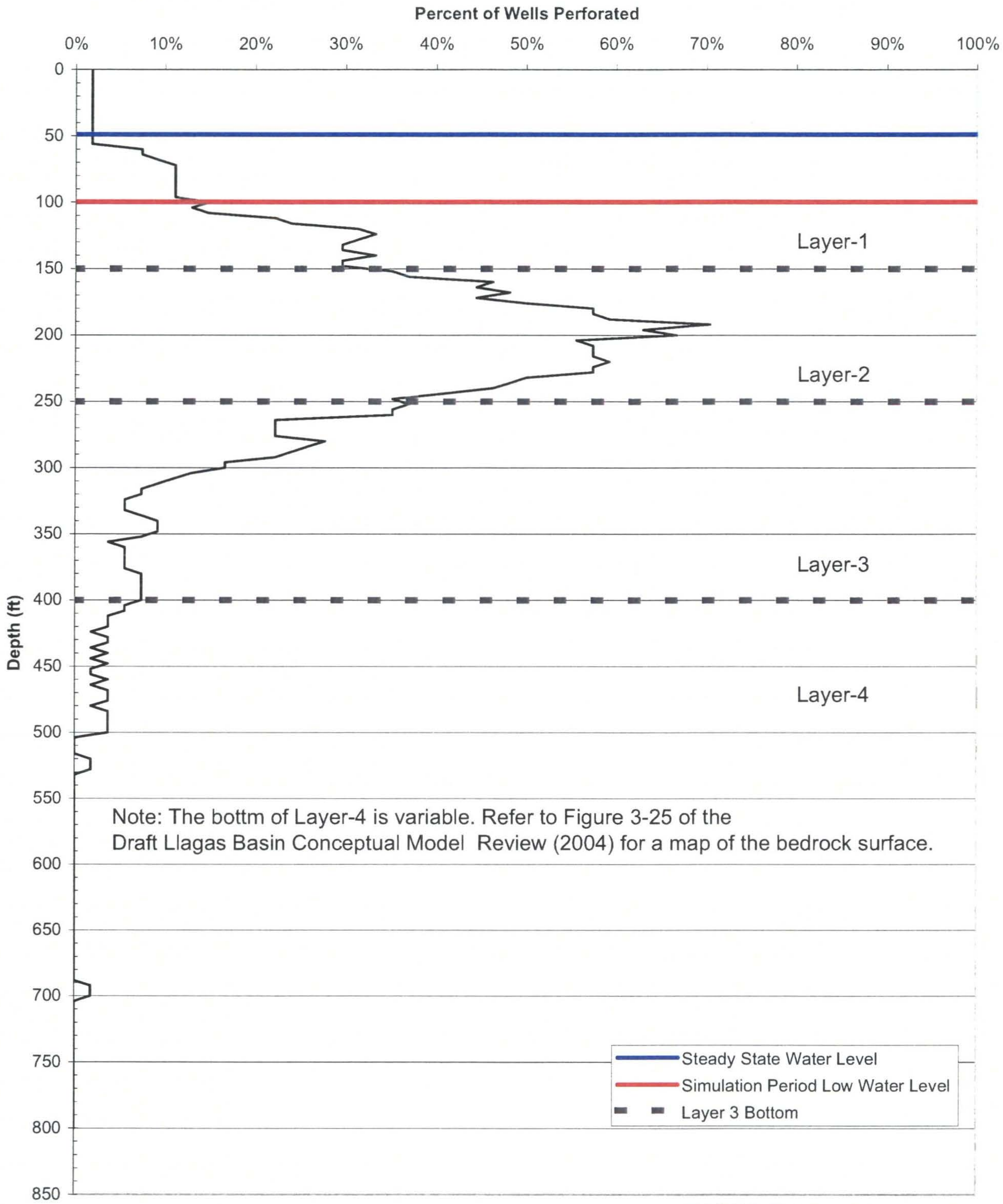


Screen_Frequency_Plots.xls -- C-PercentWells_10S03E (3) -- 06/17/2004

FIGURE 2-3
PRODUCTION WELL PERFORATIONS WITH DEPTH
10S03E WELLS (108 WELLS)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



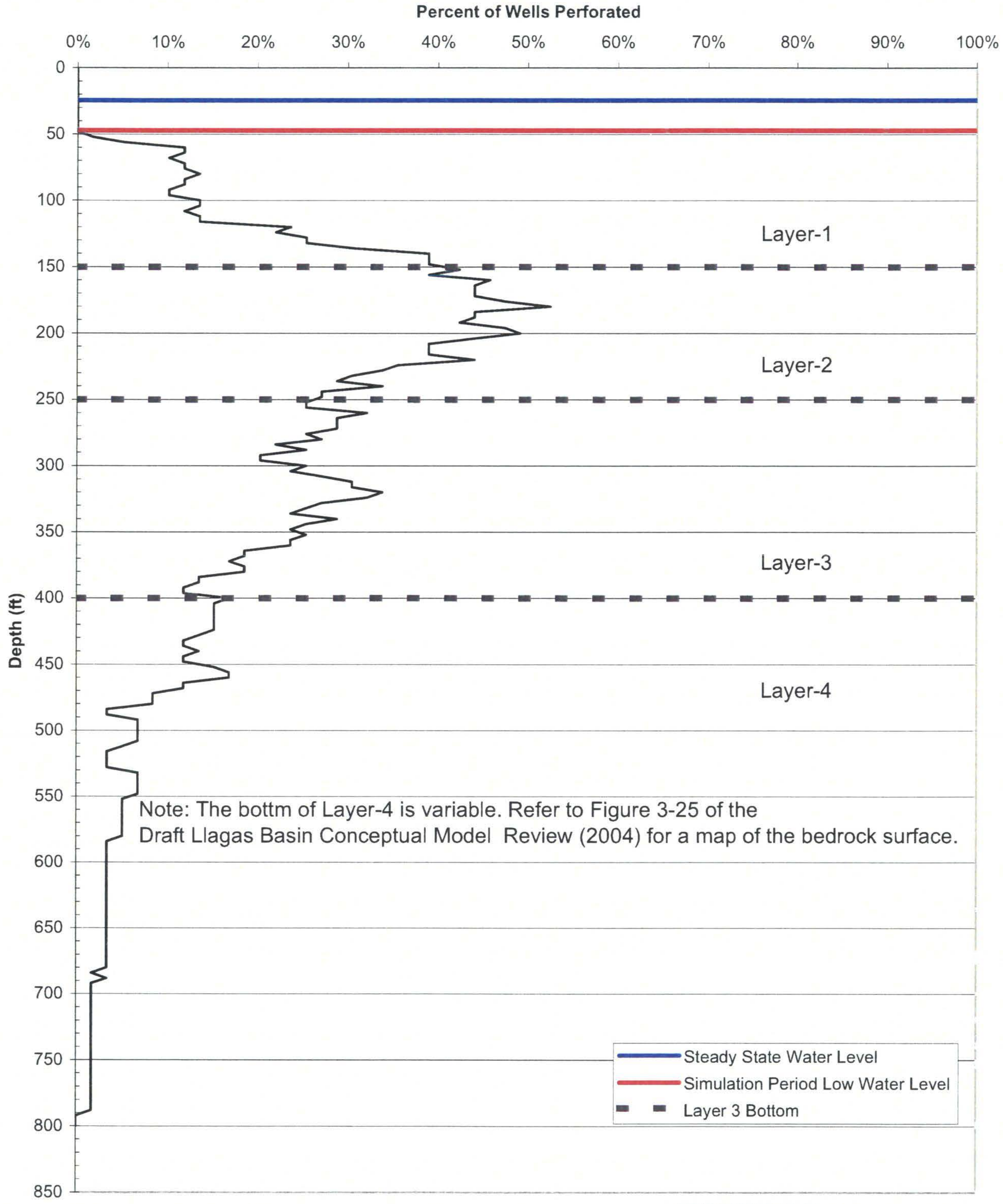
Note: The bottm of Layer-4 is variable. Refer to Figure 3-25 of the Draft Llagas Basin Conceptual Model Review (2004) for a map of the bedrock surface.

FIGURE 2-4
PRODUCTION WELL PERFORATIONS WITH DEPTH 10S04E WELLS (54 WELLS)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Screen_Frequency_Plots.xls -- C-PercentWells_10S04E (3) -- 06/17/2004

CH2MHILL



Note: The bottm of Layer-4 is variable. Refer to Figure 3-25 of the Draft Llagas Basin Conceptual Model Review (2004) for a map of the bedrock surface.

FIGURE 2-5

PRODUCTION WELL PERFORATIONS WITH DEPTH 11S04E WELLS (54 WELLS)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Screen_Frequency_Plots.xls -- C-PercentWells_11S04E (3) -- 06/17/2004

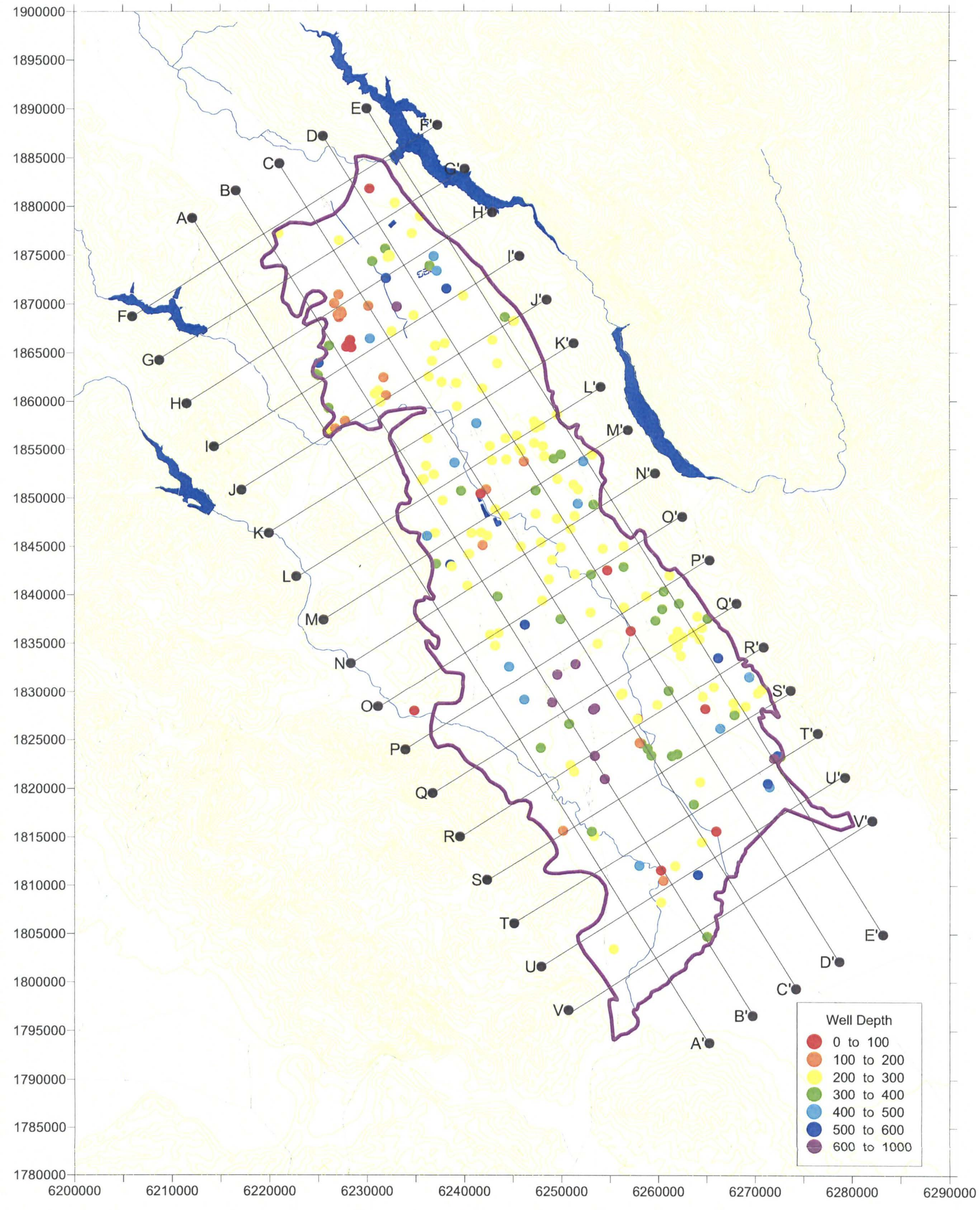
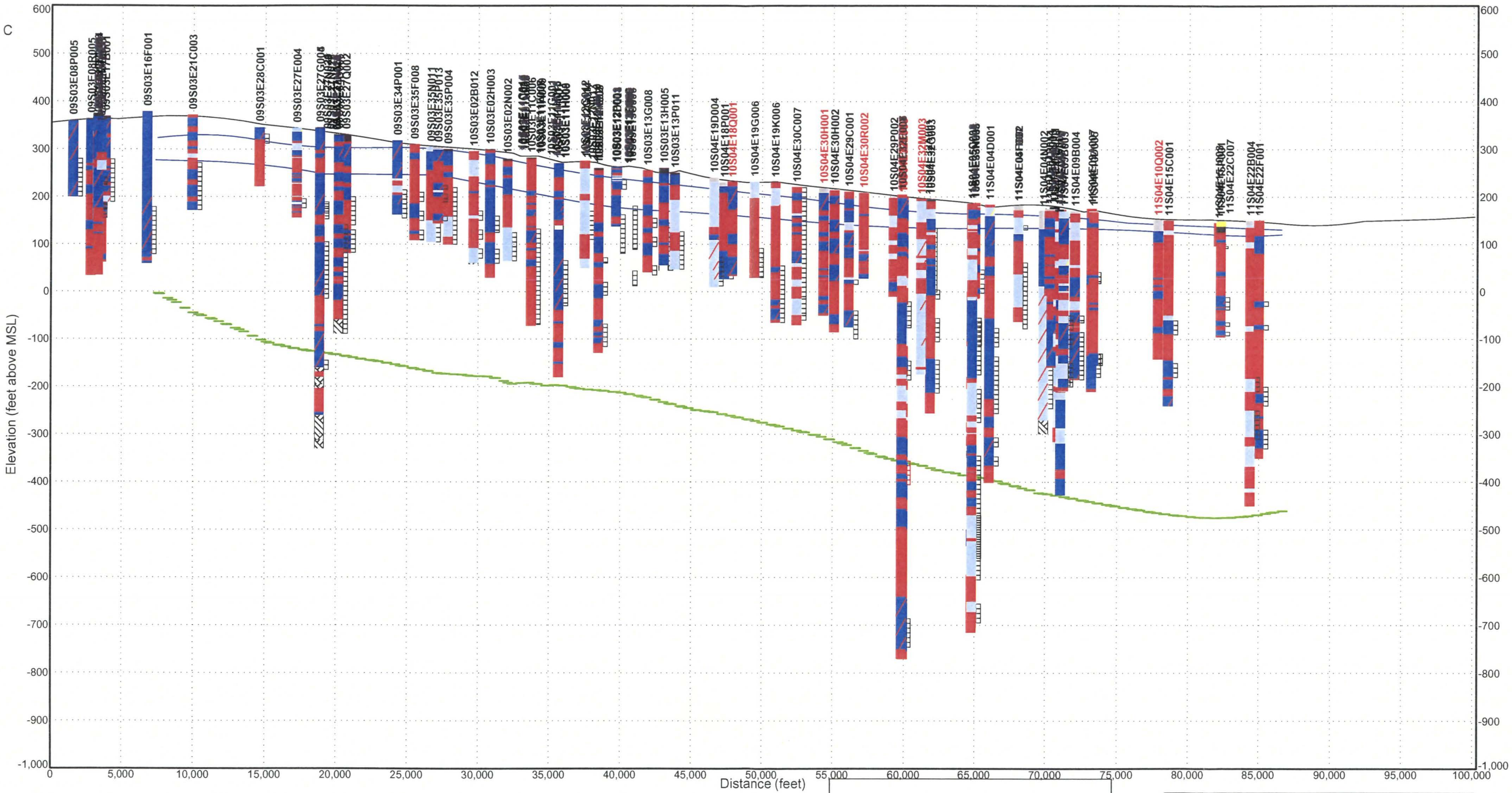


FIGURE 2-6
CROSS SECTION LOCATIONS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409 LB 05_Fig 2-6_5/12/05_ccc_sfo

CH2MHILL



▥ Well Screen

Legend

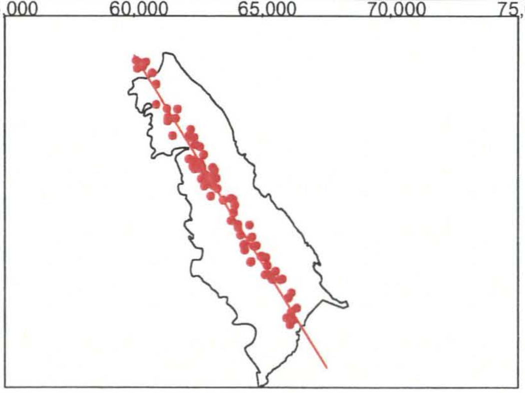
▨ BR

🟦 GP ☐ SP 🟨 ML 🟥 CL

🟦 GW ☐ SW 🟨 MH 🟥 CH

▨ GM ▨ SM ☐ FL ■ OH

▨ GC ▨ SC ■ PT ■ OL



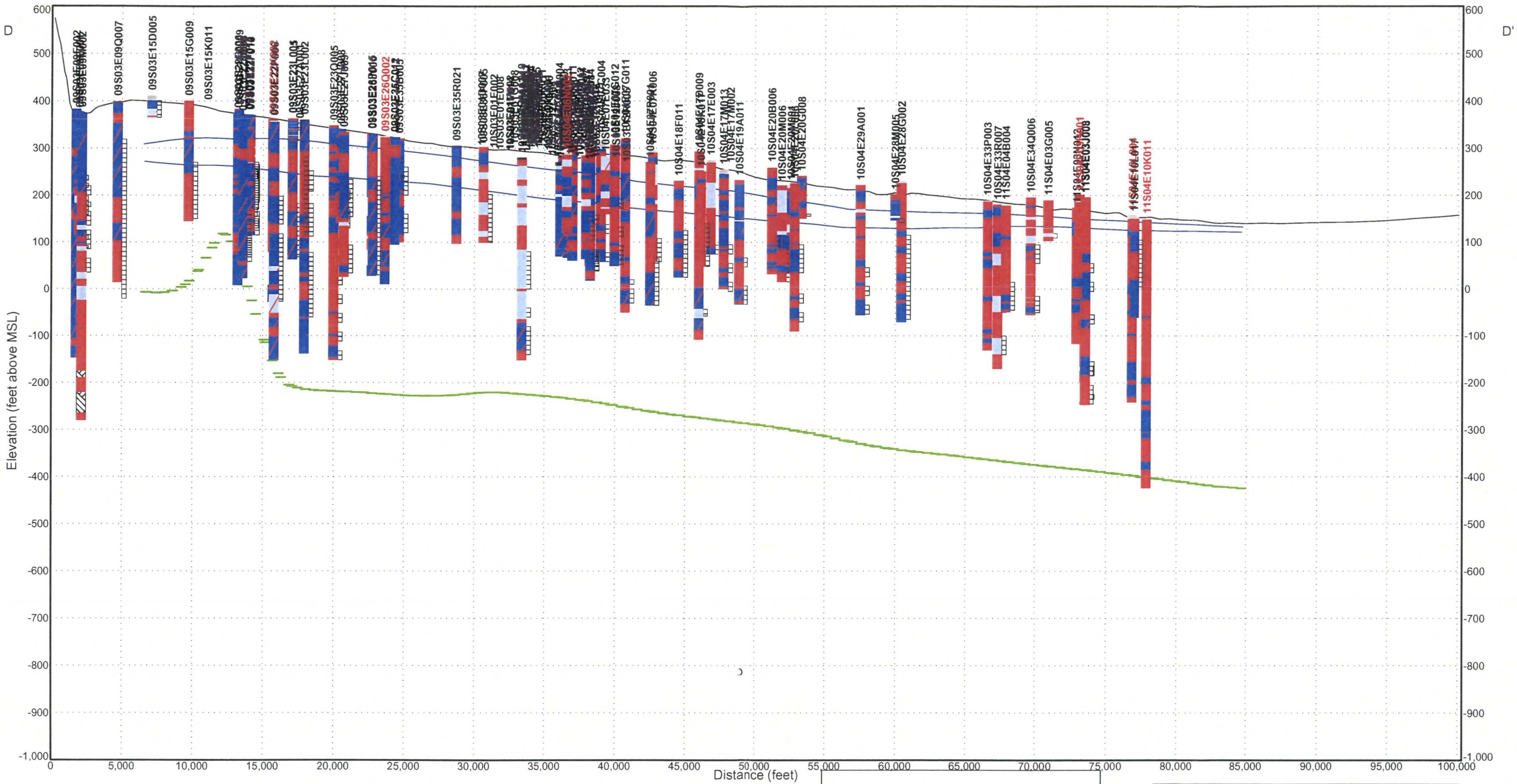
XSection C-C'

Santa Clara Valley

Date: 02 Mar 04 | Figure

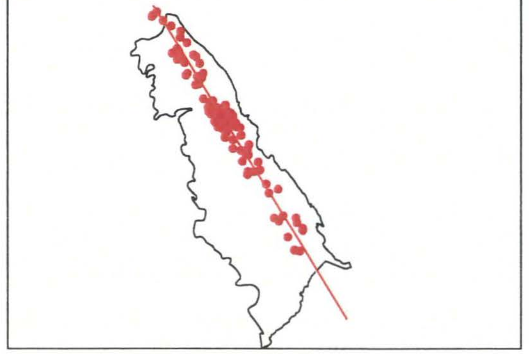
G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/19/2004

FIGURE 2-7
CROSS SECTION C-C'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL



Legend

- ▤ Well Screen
- 🟦 GP
- 🟦 GW
- ▨ GM
- ▨ GC
- ▢ SP
- ▢ SW
- ▨ SM
- ▨ SC
- 🟨 ML
- 🟨 MH
- ▢ FL
- ■ PT
- ▨ BR
- 🟥 CL
- 🟥 CH
- ■ OH
- ■ OL



G:\SANTACLARAVALLEYWATE\188409\GINT\SANTACLARA.GPJ
G:\SANTACLARAVALLEYWATE\188409\GINT\LIBRARY_SC.GLB
GS_ELEV_LONG
3/19/2004

XSection D-D'
Santa Clara Valley
Date: 02 Mar 04	Figure

FIGURE 2-8
CROSS SECTION D-D'
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT
CH2MHILL

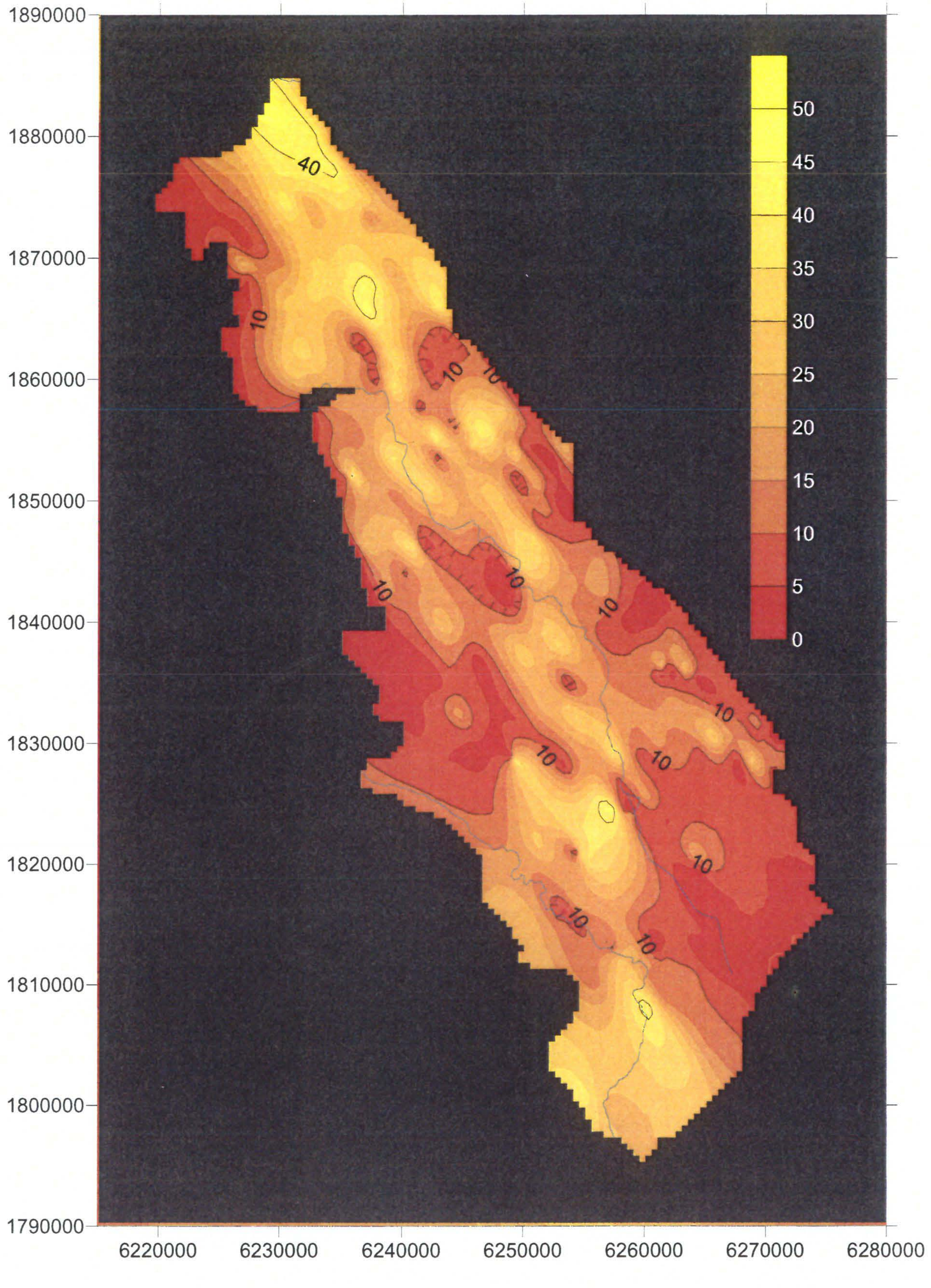


FIGURE 2-9
HYDRAULIC CONDUCTIVITY (ft/d) DISTRIBUTION LAYER-1

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

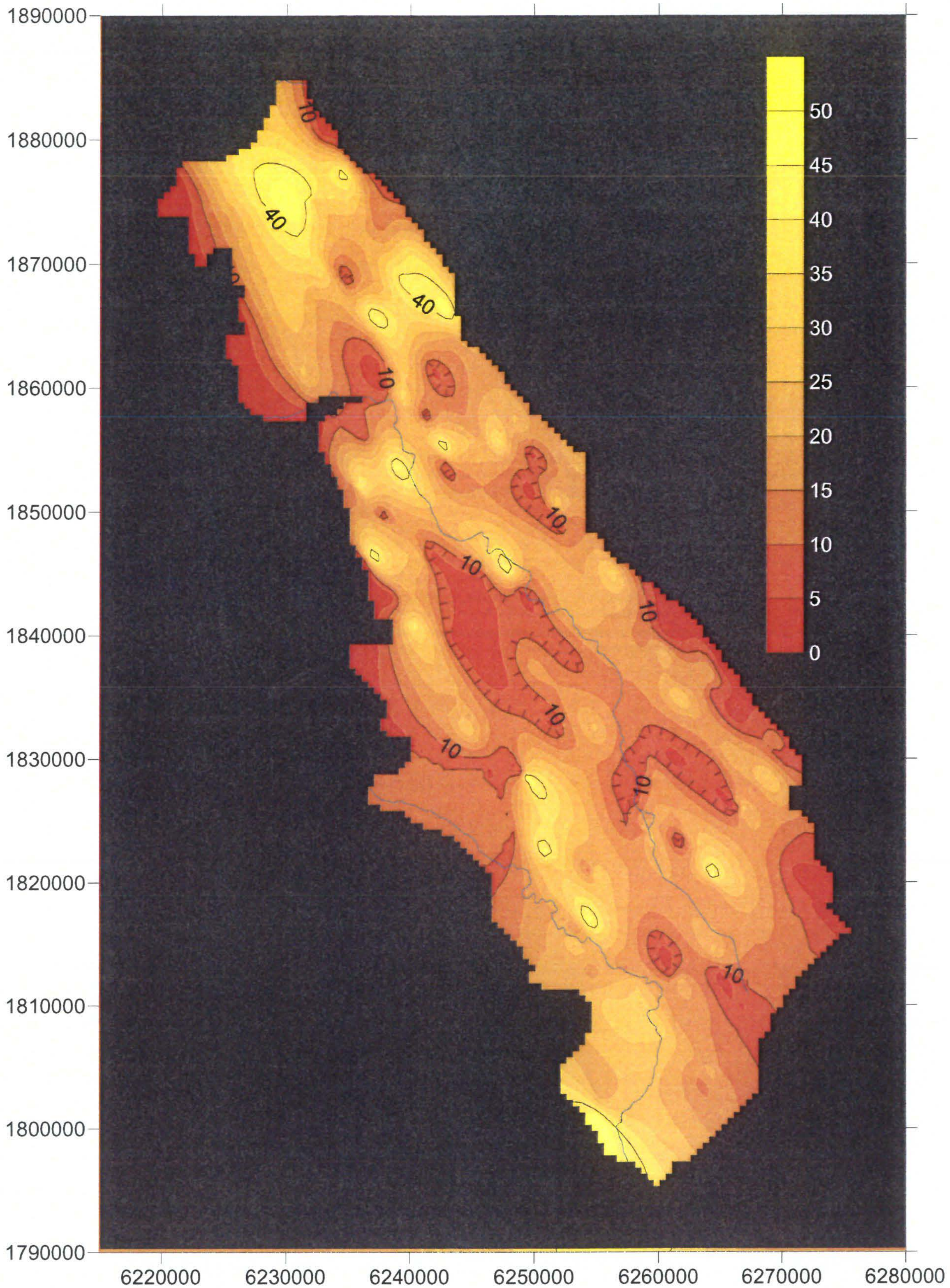


FIGURE 2-10
HYDRAULIC CONDUCTIVITY (ft/d) DISTRIBUTION LAYER-2

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 2-10__5/12/05_ccc_sfo

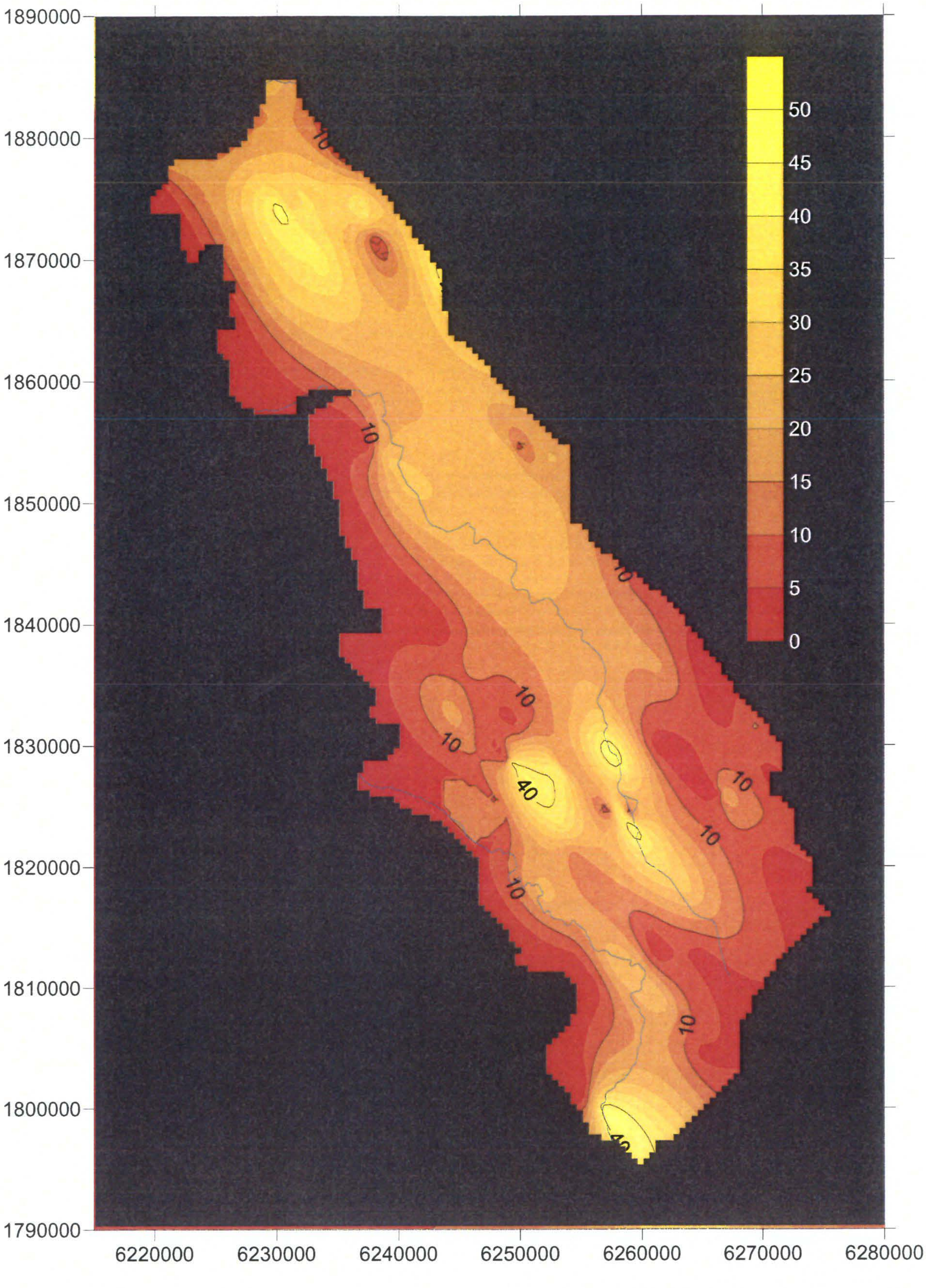


FIGURE 2-11
HYDRAULIC CONDUCTIVITY (ft/d)
DISTRIBUTION LAYER-3
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

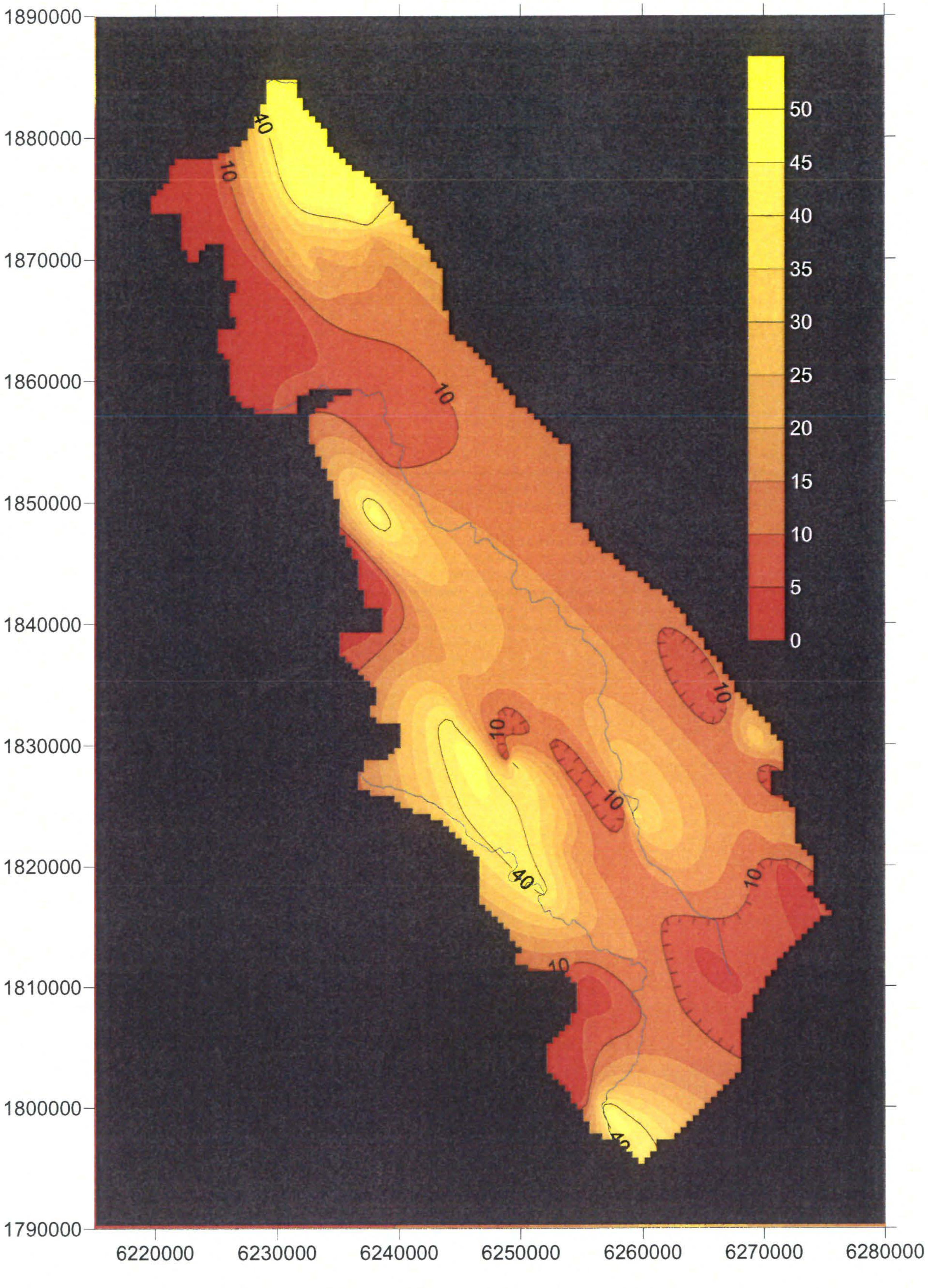


FIGURE 2-12
HYDRAULIC CONDUCTIVITY (ft/d) DISTRIBUTION LAYER-4

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

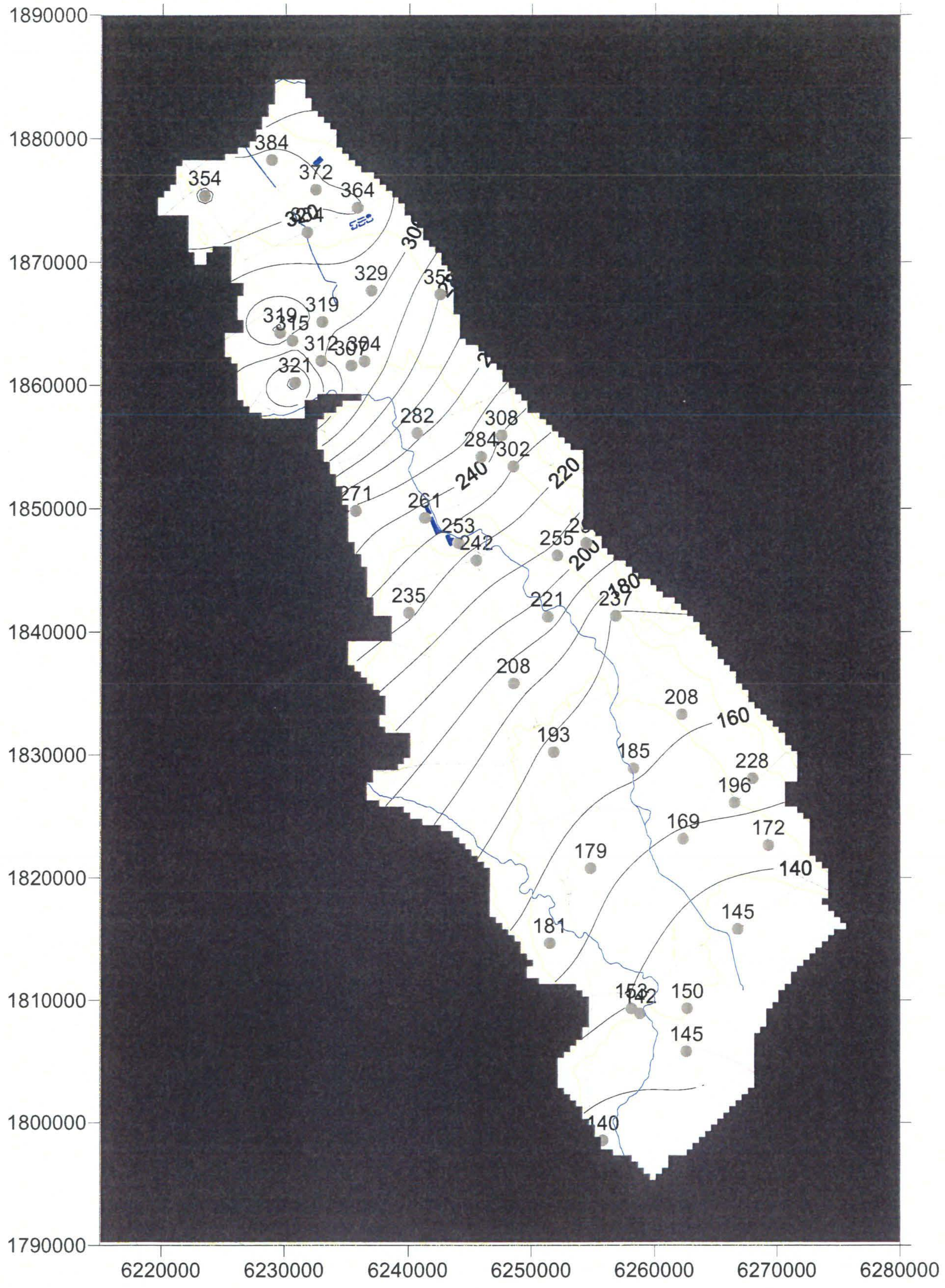


FIGURE 2-13
STEADY STATE WATER LEVEL TARGETS
WATER-YEARS 1996-98
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409.LB.05_Fig 2-13__5/12/05_ccc_sfo

CH2MHILL

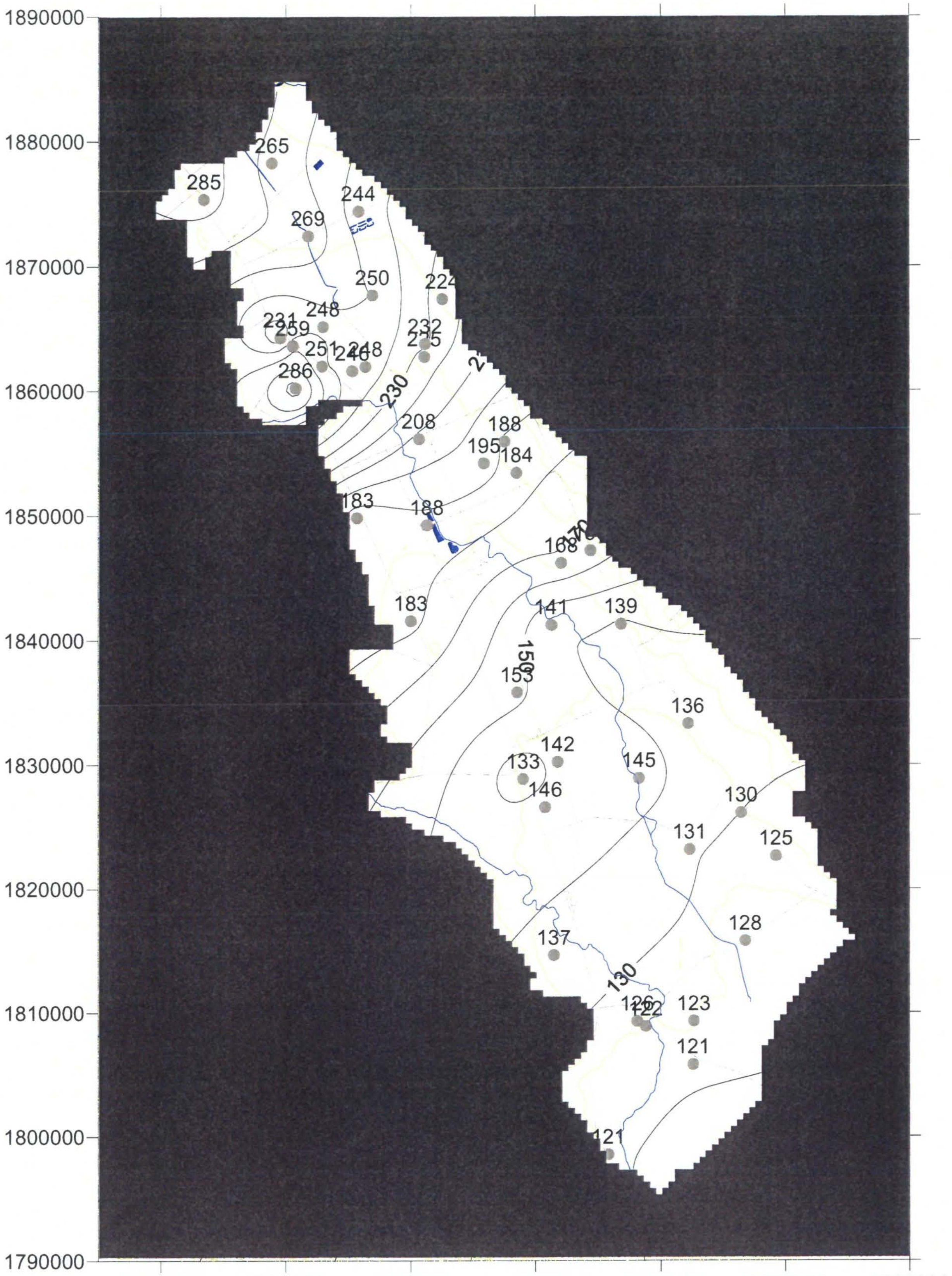
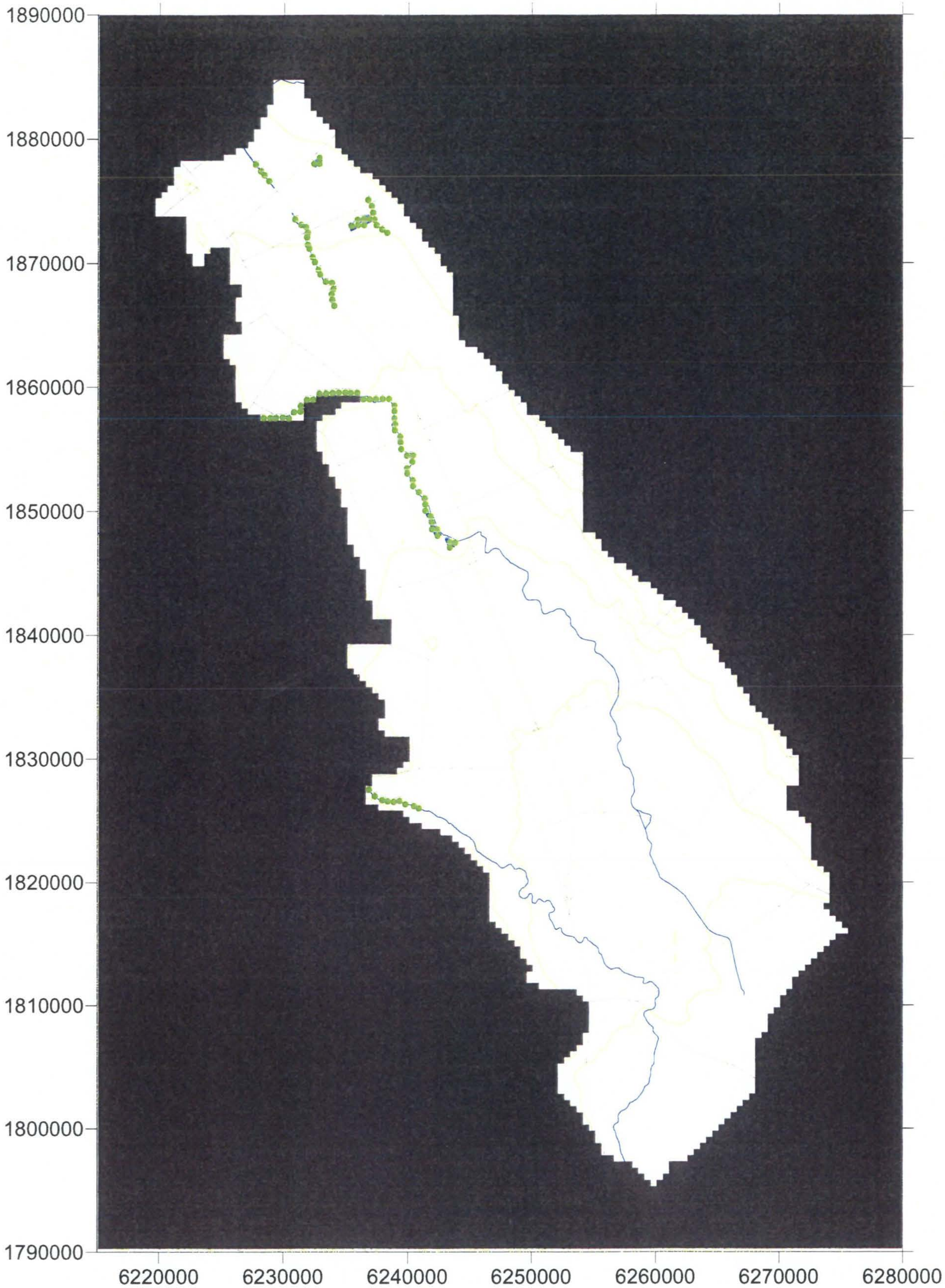


FIGURE 2-14
INITIAL CONDITIONS WATER LEVEL MAP
FOR TRANSIENT SIMULATION
WATER-YEAR 1988
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT



● Well Used to Simulate Intentional Recharge

FIGURE 2-15
LOCATION OF WELLS USED TO SIMULATE INTENTIONAL RECHARGE

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 2-15__5/12/05_ccc_sfo

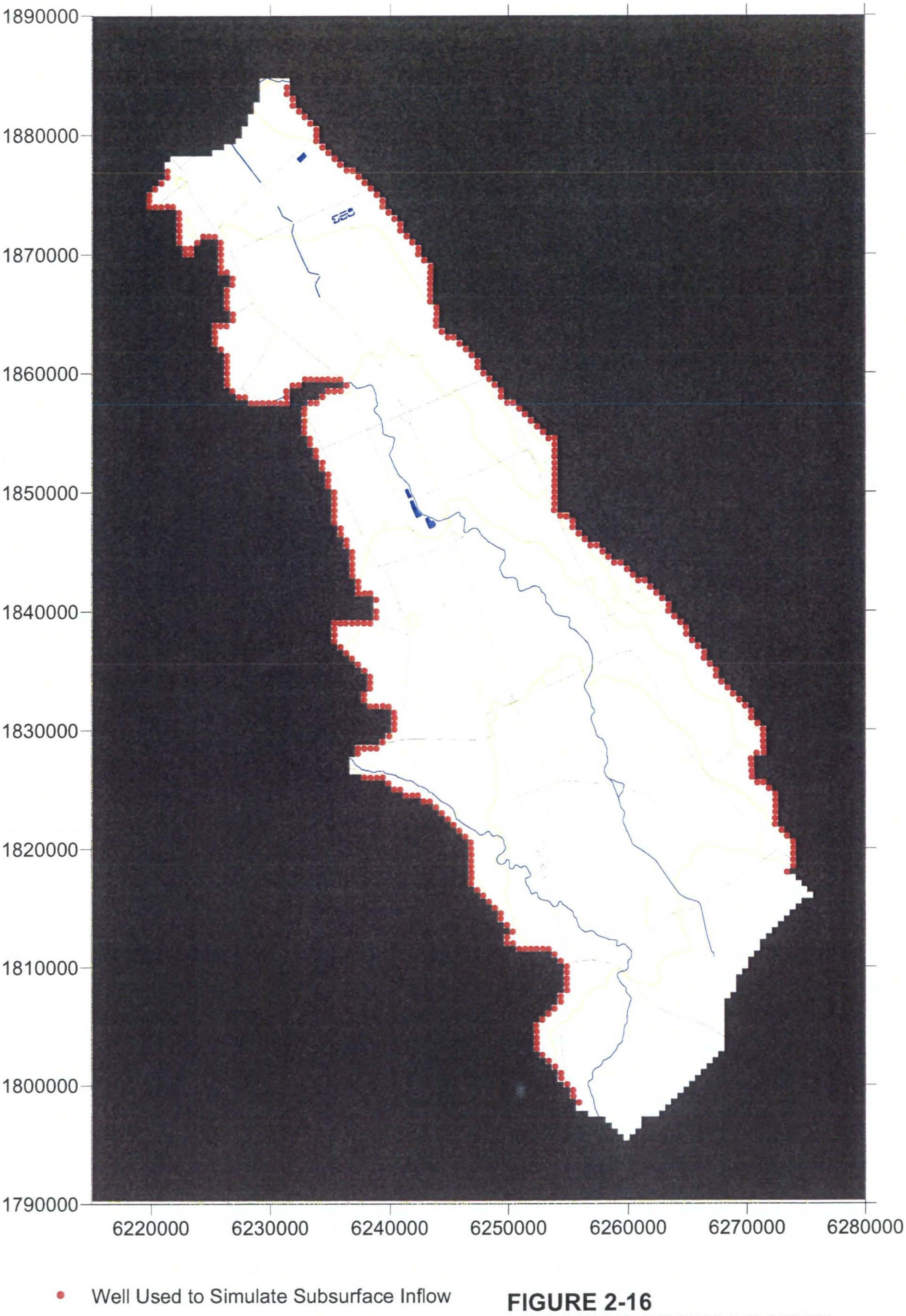
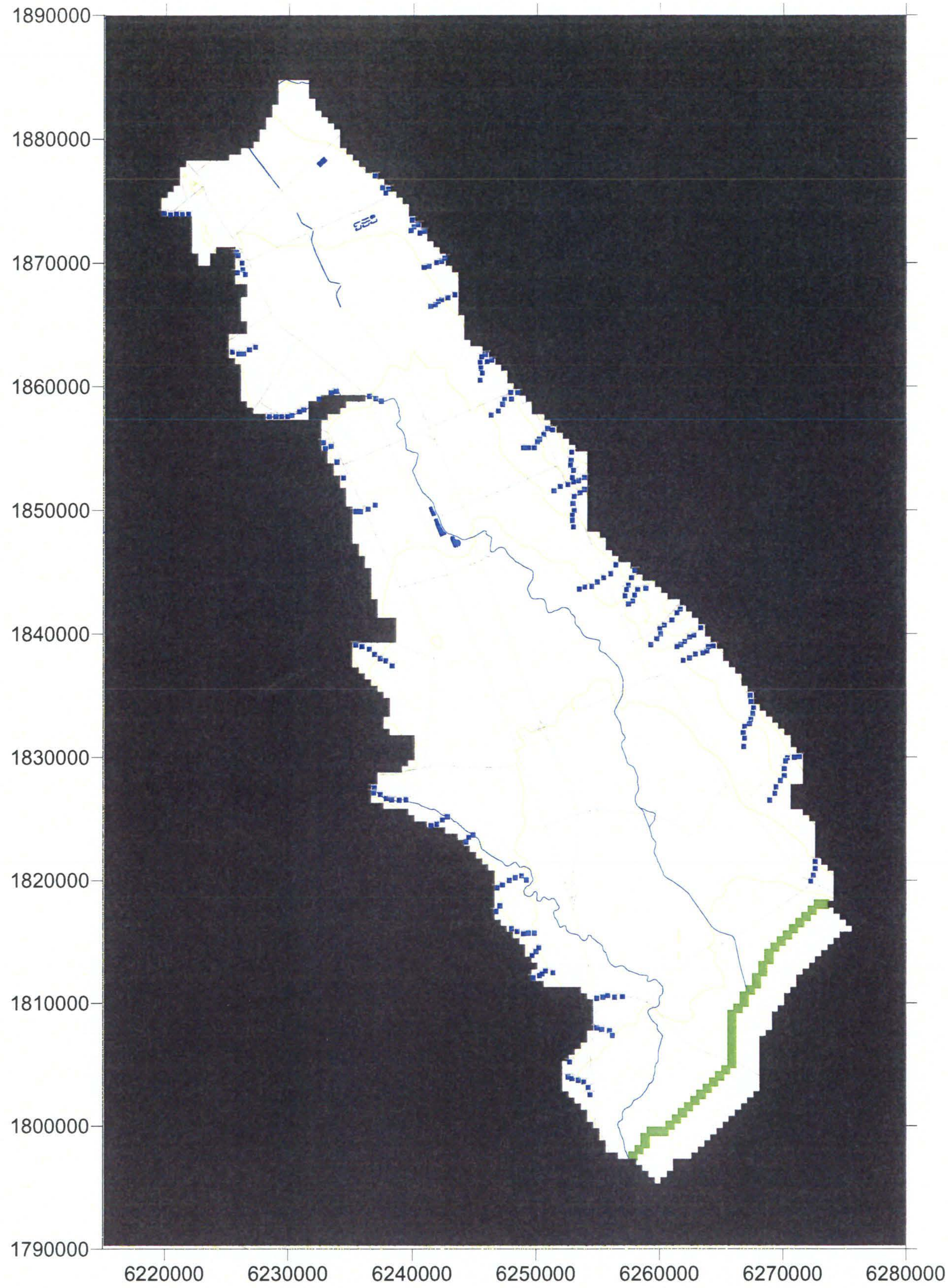


FIGURE 2-16
LOCATION OF WELLS USED TO SIMULATE SUBSURFACE INFLOW

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 2-16__5/12/05_ccc_sfo



● Well Used to Simulate Stream Seepage

🟩 Pajaro River (MODFLOW River Package)

FIGURE 2-17
PAJARO RIVER AND STREAM SEEPAGE

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 2-17__5/12/05_ccc_sfo

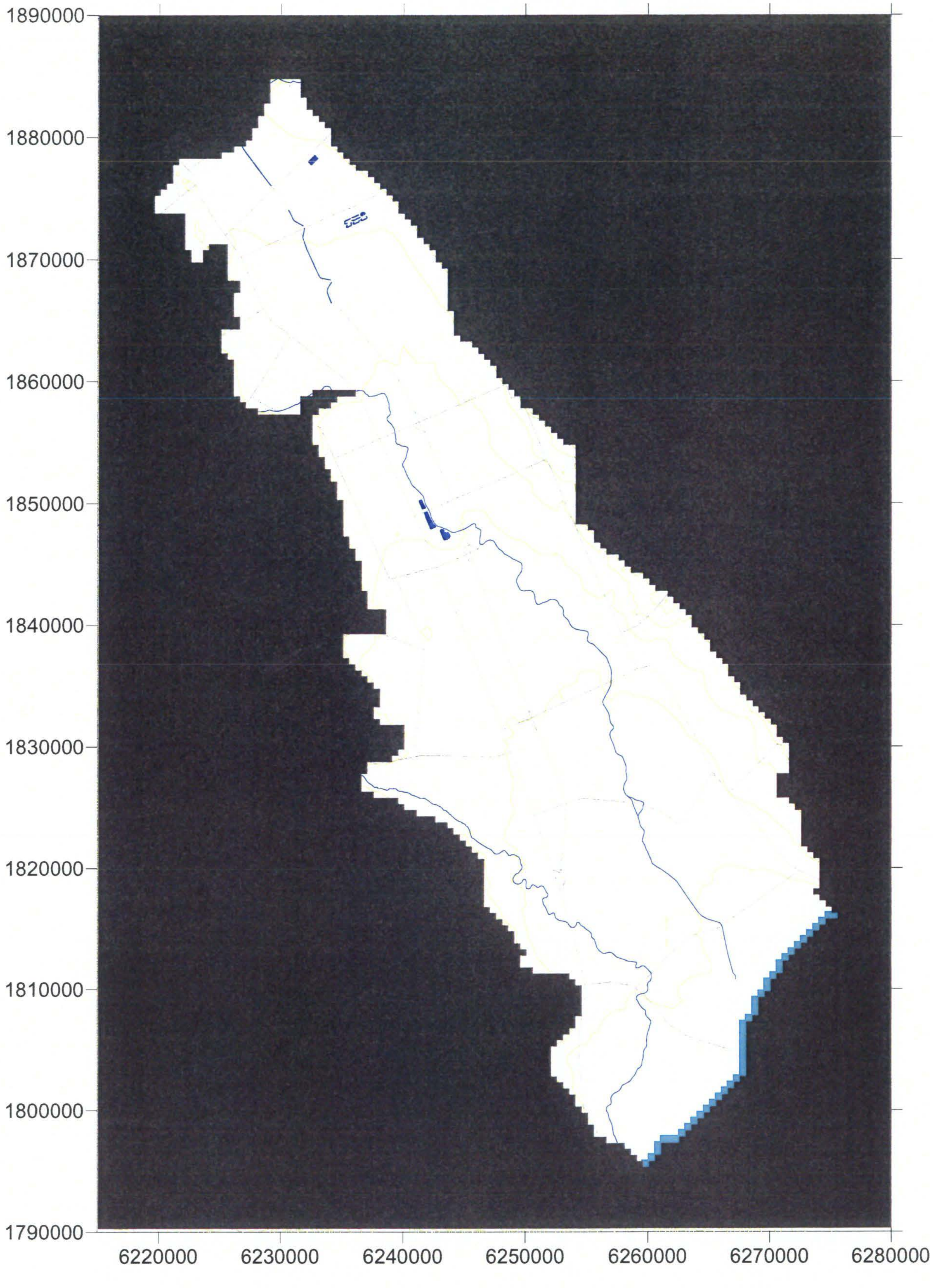


FIGURE 2-18
GENERAL HEAD BOUNDARY

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 2-18__5/12/05_ccc_sfo

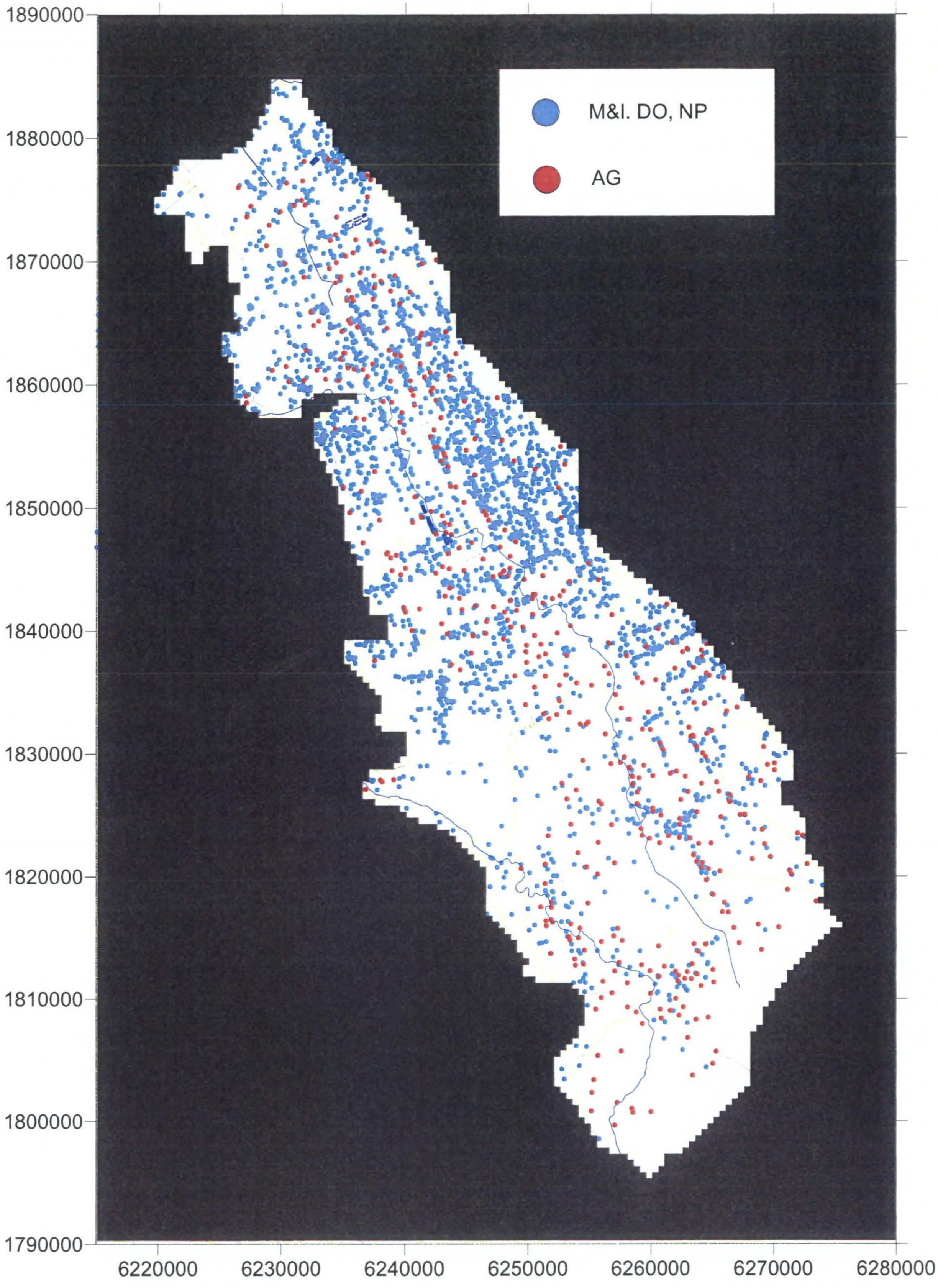


FIGURE 2-19
PUMPING WELLS

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

SECTION 3

3.0 Model Calibration

3.1 Introduction

This section describes the methods and results of model calibration. A copy of the electronic files developed for the modeling and a brief explanation of how these files are used are presented in Appendix B.

Model calibration consisted of both manual and automated inverse techniques. Manual calibration was performed using the MODFLOW-2000 (CH2M HILL, 2000) code for groundwater simulation and the PEST code to perform inverse calibration and assess uncertainty. MODFLOW-2000 is an updated version of the well-known and widely used MODFLOW code developed by the U.S. Geological Survey in 1988. It was developed to solve several groundwater equations in an integrated fashion, including those dealing with flow, transport, and inverse modeling. The PEST code is a model-independent inverse parameter estimator with powerful predictive analysis.

3.2 Calibration Methods

3.2.1 Steady-state Calibration

Average conditions in the basin during water years 1996-98 were originally identified for use in the steady-state calibration (CH2M HILL, 2004b). Hydrographs for wells in the basin indicated that the mid-1990s was a period of relatively steady-state water levels and were therefore used as the basis for steady-state calibration. However, contrary to the severe drought experienced in the basin during the 1980s, climatic conditions in the basin during the mid-1990s were some of the wettest this century. Though observed water levels appear to be temporarily stable during this period, the basin was full, and some water budget components were at a maximum state relative to the period of record. Because climatic conditions during the period of calibration transitioned from one extreme to another, a true steady-state period could not be simulated for calibration. The rapid transition across two climatic extremes (dry to wet) during the period for which flux data exist prohibited a meaningful steady-state calibration.

3.2.2 Transient Calibration

Transient calibration was performed for a 15-year period beginning in water year 1988 and terminating at the end of water-year 2002. Principal parameters adjusted during transient calibration were:

- Hydraulic conductivity
- Storage coefficients for Layer-1 through Layer-4
- Areal recharge (deep percolation of precipitation and water applied for agricultural irrigation)

- Subsurface inflow from bedrock
- Representation of Llagas and Uvas Creeks, and the Pajaro River

A summary of the model parameters changed during calibration is presented in Tables 3-1a and 3-1b. These parameters were adjusted to match two sets of primary calibration targets:

- Transient water levels - observed head data covering the entire 15-year span of historical calibration from 40 calibration wells and flow direction
- Water budget – flow to and from creeks and rivers, flow to drains, and subsurface flow from and to Bolsa Basin

Transient Water Levels

Select calibration hydrographs showing the relationship of observed and computed heads are shown in Figures 3-1 and 3-2. A complete set of hydrographs is presented in Appendix C. These figures indicated generally good agreement between simulated and observed groundwater levels at the calibration wells. Overall, simulated groundwater levels follow trends in observed groundwater levels, and the magnitude of groundwater level rises and declines are generally preserved.

A plot of observed versus simulated water levels for all wells with water level data in the basin also suggest good correlation among residuals (Figure 3-3). The 45-degree line represents a perfect match. The limited amount of scatter around this line is indicative of a good fit between observed and simulated water levels. Based on these data, statistics were used to quantitatively evaluate the degree of correspondence between the modeled and observed data; or residuals (see Figure 3-3). The calibration statistics also indicate a high degree of correspondence between modeled and observed water levels through time. Root mean squared (RMS) error, or standard deviation, is the average of the squared residuals. The RMS over the magnitude of the change in observed heads over the problem domain (Range) is typically regarded as the best measure of error if the errors are normally distributed. Values of RMS/Range less than 10 percent are considered good. The RMS/Range for the final calibration was 4.4 percent.

Particle tracking was used to evaluate general groundwater flow direction. Particle tracking simulations were based on a recent map of perchlorate distribution in the basin (Figure 3-4). Particles were started at the known source of the perchlorate contamination, and permitted to migrate for 55 years (the estimated time since perchlorate was released into the groundwater system). Since historical fluxes and basin hydrology were not available for the entire 55-year period, particle tracking was based on a representative 5-year transient period (water year 1988 to water year 1993) when average fluctuations in observed water levels roughly match historically observed water levels over the 55-year period. Results of particle tracking are presented in Figure 3-5. Simulated groundwater flow direction corresponds well to the direction inferred from the observed perchlorate distribution. Particle tracking simulates advective (or average) flow and does not account for the effects of dispersion. This may explain the differences in simulated width and length of perchlorate migration.

Table 3-1a Model Parameters Changed During Manual Calibration

Llagas Basin Groundwater Model

Model Parameter		Calibration Run Number																			
		11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Transient (T) or Steady State (S)		T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
MT3D Run Performed																					
MODPATH																					
Borehole Lithology Method																					
Uncertainty Analysis																					
Based on PEST Run						105		116		118											
Based on Manual Run		10	11	12	13		15		17		19	20	21	22	23	24	24	25	20	28	27
Hydraulic Conductivity	Zones																				
	Pilot Points																				
Specific Yield	Single Zone				●				●							●			●		
	Mult. Zones																●				
Dispersivity																					
Porosity																					
Anisotropy											●										
Specific Storage								●			●							●		●	
Areal Recharge Fluxes				●								●	●	●	●						●
ET																					
Drain																					
Well Fluxes	In																				
	Out																				
Streams	Fluxes																				
	Conductivity									●											
	Location																				
General Head Boundary	Conductivity									●											
	Location																				●
Target Layers																					
Initial Heads			●			●	●														
Numerical Instability																					
Notes		First transient model run. Previous model runs are part of the initial model development.																			

Model Parameter		Calibration Run Number																					
		31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	49a	49b	49c
Transient (T) or Steady State (S)		T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	S	T	T	T
MT3D Run Performed																							
MODPATH																			●	●			
Borehole Lithology Method																							
Uncertainty Analysis																							
Based on PEST Run																	120		128				
Based on Manual Run		30	31	27	33	34	35	36	37	37	39	40	40	42	43	44		46		48	48	49a	49a
Hydraulic Conductivity	Zones																						
	Pilot Points																						
Specific Yield	Single Zone																						
	Mult. Zones						●	●	●			●											
Dispersivity																							
Porosity																						●	●
Anisotropy		●						●															
Specific Storage																							
Areal Recharge Fluxes										●	●					●		●					
ET														●									
Drain																	●						
Well Fluxes	In																						
	Out																						
Streams	Fluxes					●							●										
	Conductivity				●										●								
	Location			●																			
General Head Boundary	Conductivity																						
	Location		●																				
Target Layers																							
Initial Heads																							
Numerical Instability																							
Notes																							

Model Parameter		Calibration Run Number																	
		50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
Transient (T) or Steady State (S)		T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
MT3D Run Performed		●	●	●															
MODPATH							●	●	●										
Borehole Lithology Method																			
Uncertainty Analysis		●	●	●	●	●	●	●	●										
Based on PEST Run					128					133	58	59	60	59	62	63	64	64	66
Based on Manual Run		48	50	51		53	54	55	56										
Hydraulic Conductivity	Zones																		
	Pilot Points																		
Specific Yield	Single Zone											●				●	●		
	Mult. Zones									●									
Dispersivity				●															
Porosity																			
Anisotropy																			
Specific Storage																			
Areal Recharge Fluxes																			
ET																			
Drain																			
Well Fluxes	In				●	●													
	Out																		
Streams	Fluxes										●		●	●	●			●	●
	Conductivity																		
	Location										●							●	●
General Head Boundary	Conductivity																		
	Location																		
Target Layers																			
Initial Heads																			
Numerical Instability							●	●	●										
Notes			Used HMOC solver instead of finite difference								Added RIV package to upper Llagas Creek								

Table 3-1b Model Parameters Changed During Automated Inverse Calibration (PEST)
Llagas Basin Groundwater Model

Model Parameter		Calibration Run Number																																									
		101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	130a	131	132	132a	133	133a	134	135	136	137	138	139	140	141
Transient (T) or Steady State (S)		T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
MT3D Run Performed																																													
MODPATH																																													
Borehole Lithology Method																																						●			●	●	●	●	●
Uncertainty Analysis																															●	●	●	●	●										
Based on PEST Run			101		103	102	104	104	105	107	109	110	110	108	113	112	108	116	117			120	121	120	123	124		126	127	128	128	130	128	128	132		133	128	64		134	64	138	138	138
Based on Manual Run		11		14																20	45						47				54					53									
Hydraulic Conductivity	Zones	o	o	o	o	o			o					o	o		o	o	o	o	o	o	●	●	●		o			o	o	o		o	o	o	o	o	o		o	o	o	o	o
	Pilot Points							o		o	o	o	o			o												o	o																
Specific Yield	Single Zone				o	o		o											●																										
	Mult. Zones								o	o	o	o	o	o	o	o	o	o			o	●	o	●	●		o				o	o		o	o	o	o		o						
Dispersivity																																													
Porosity																																													
Anisotropy			●							●	●	●	●																			●			●										
Specific Storage											●				●																														
Areal Recharge Fluxes							o						●					●						o	o		●							●			●								
ET																																													
Drain																																													
Well Fluxes	In																														●					●									
	Out															●	●																												
Streams	Fluxes																																												
	Conductivity																																												
	Geometry																																												
General Head Boundary	Conductivity																																												
	Location																																												
Target Layers											●			●																															
Initial Heads										●																																			
Numerical Instability							●							●		●										●							●												
Notes		First inverse run		Return to PEST after two "manual" sensitivity runs with new recharge			First attempt at having PEST estimate recharge			Used updated initial heads file and increased number of pilot points	Errors made in Run 108 are corrected here					PEST could not find a lower value of phi onteh first iteration and crashed				Modifications from R020 are incorporated into a PEST run	Modifications from R045 are incorporated into a PEST run			Estimating Recharge Using PEST	Estimating Recharge Using PEST				Results of this run were presented to SCVWD in a presentation Aug. 2004		Vertical anisotropy ration not maintained	Maintained vertical anisotropy		Vertical anisotropy ration not maintained	Maintained vertical anisotropy	Delivered to SCVWD Sept. 2004			Used alternative calibration with higher value of Sy (10-percent)		Tie the bedrock parameter to the gravel parameter	Used alternative calibration with higher value of Sy (10-percent)			

o - Parameter estimated by PEST
• - Parameter changed for run

Water Budget

Average groundwater fluxes into and out of the basin were identified and estimated during conceptual model development (CH2M HILL, 2004a). During the calibration process, key specified water budget components, such as subsurface inflow from bedrock and deep percolation of precipitation and water applied for agricultural irrigation, were adjusted (see Tables 3-1a and 3-1b). Other water budget components, such as subsurface outflow to Bolsa Basin and discharge to creeks, were calculated by the model during calibration and checked to make sure values fell within a reasonable range. Individual specified water budget components were assigned a range of realistic values that might be expected in the basin over the 15-year calibration period. These water budget components served as water budget calibration parameters. Final simulated values of recharge and discharge for each stress period are summarized in Figure 3-6.

In general there is good correspondence between estimated and simulated fluxes into and out of the basin (Figure 3-7). Differences exist in the addition of a few water budget components that were not identified during conceptual model development. This primarily includes groundwater seepage to land surface (drains) and groundwater discharge to creeks. These water budget components are only active during the wet winter stress periods in the mid-1990s and are not significant components of the budget on average. A notable difference also exists with groundwater pumping. Pumping numbers cited in the conceptual model include wells located in the smaller tributary basins located outside the model active area, which accounts for this discrepancy.

Properties

Simulated aquifer properties and water budget components fell within realistic ranges for the physical hydrogeologic system, as defined during conceptual model development. Figures 3-8 and 3-9 show the final hydraulic conductivity and transmissivity distributions. As discussed in Section 2.3, Hydrogeologic Properties, the borehole lithology method was used to initially distribute aquifer properties in the basin. Attempts to calibrate the model using this method did not yield realistic results. Instead, aquifer properties were initially distributed based on limited pumping test and specific capacity data. Final transmissivity distribution corresponds reasonably well to specific capacity data available for production wells in the basin, especially in the area around the City of Gilroy where the data are more reliable (Figure 3-10). Final transmissivity values are generally higher than those estimated from specific capacity data because they are based on the entire saturated thickness of the basin, whereas the wells with specific capacity information are screened across a small portion of the total saturated thickness. For example, screen lengths of wells with specific capacity data in the central and north portions of the basin range from about 50 to 230 feet, but saturated thickness in these areas is between 400 and 500 feet. The ratio of vertical to horizontal hydraulic conductivity was also adjusted during the calibration process (see Tables 3-1a and 3-1b). Final calibration yielded a ratio of 1:100. Reasonable ratios of vertical to horizontal hydraulic conductivity range between 1:10 and 1:1000 (Anderson and Woessner, 1992).

Values of specific yield in model Layer-1 range from 0.005 to 0.01 (Figure 3-11) and specific storage for model Layer-2 through Layer-4 are assigned a uniform value of 2E-5. Values of specific yield are lower than what is typical for an unconfined aquifer system. Numerous approaches were used to increase specific yield using manual and inverse calibration procedures, including adjusting the quantities of some existing water budget components. Results of these attempts yielded simulated water levels that did not respond to seasonal pumping influences or, more importantly, to long-term water level trends caused by macro-scale changes in the basin's climate. To address this issue, an alternative concept was developed, which assumes Llagas Creek recharges groundwater in winter months during excessively wet periods similar to those experienced in the basin during the mid-1990s. Using this concept, specific yield in Layer-1 was increased to 10 percent while long-term water level trends were preserved. A complete summary of this approach is presented in Appendix D. Implementing this approach yields a more realistic value of long-term specific yield, but there are no observed data to support or refute this new concept. Use of the higher value of specific yield is more appropriate for predicting long-term (year or more) basin response. The smaller values are appropriate for simulating shorter-term (six months or less) events like pumping tests or seasonal responses.

3.3 Uncertainty Analysis

Model uncertainty is an issue of profound importance that is often overlooked and improperly evaluated. Uncertainty has historically been evaluated using a "sensitivity" approach, during which the model is basically thrown out of calibration and effects on model predictions evaluated. This approach can lead to mistaken conclusions regarding model reliability. Newer methods to assess uncertainty keep the model in calibration under different property distributions while assessing differences in impacts to significant model features. PEST is a tool for this type of analysis. Using PEST, two alternative calibrations were developed to assess model uncertainty and evaluate model limitations.

The two calibration alternatives were developed based on uncertainty of the recharge water budget components estimated during conceptual model development. Figure 3-12 summarizes the average distribution of key recharge components used in the final model calibration. The most significant recharge components with a large degree of associated uncertainty are subsurface inflow from bedrock and deep percolation of precipitation and water applied for agricultural irrigation. Based on the relative uncertainty with the quantity, timing, and spatial distribution of these water budget components, the following scenarios were developed for uncertainty analysis:

Scenario 1 - Subsurface inflow along the eastern margin of the model was eliminated and added to inflow along the western margin.

Scenario 2 – Deep percolation of precipitation and water applied for agricultural irrigation were reduced by 25 percent.

A summary of the results of the uncertainty analysis for each scenario are presented below.

3.3.1 Scenario 1: Redistribute Subsurface Inflow

Estimates of subsurface inflow from bedrock along mountain front areas were made based on estimates of rainfall in a particular watershed, the permeability of bedrock, the subsurface gradient, and an estimate of bedrock elevation in the basin. These estimates have not been field tested and therefore may not accurately represent the true physical system, especially as it relates to distribution of subsurface inflow. It is possible that subsurface inflow along the western margin of the basin may be significantly greater than along the eastern margin. PEST was used to assess this uncertainty. Using PEST, the model was recalibrated with the subsurface inflow from the eastern margin of the basin transferred to the western margin. This translates to a redistribution of about 7,200 afy of groundwater—a significant percentage of the total water budget.

Hydrographs showing the relationship of observed and computed heads under the new calibration appear to be very similar or the same as the hydrographs presented for the final calibration (Figure 3-13). Calibration statistics are also very similar and show that the model can be calibrated under this scenario as well as the final calibration scenario (Figure 3-14). Transmissivity distribution does not change sharply either (Figure 3-15). Since the model is equally well calibrated when distribution of subsurface inflow is significantly altered, simulated migration of the existing perchlorate plume was used to assess the impact of the uncertainty analysis. Simulation of perchlorate migration was based on average conditions similar to the previous particle tracking runs, with the exception that MT3D (Zheng and Bennett, 1995) was used to track contaminant migration. Figure 3-16 shows the extent of perchlorate migration under each calibration scenario.

Despite being equally well calibrated and having similar transmissivity distributions, the two models differ in their prediction of perchlorate migration. The impact of redistributing subsurface inflow is manifested in the model's prediction of perchlorate migration in groundwater. The final calibration more closely mimics observed perchlorate distribution.

3.3.2 Scenario 2: Decrease Areal Recharge by 25 Percent

Estimates of deep percolation of precipitation and water applied for agricultural irrigation are largely dependent on the type of land use in the basin. For example, areas of truck crops in the basin yield far more recharge than those designated as native vegetation. Since land use maps were only available for two years (1990 and 1998), a significant amount of uncertainty lies in the estimates of land use for the remaining calibration period. This in turn creates uncertainty in the estimates of recharge via deep percolation of precipitation and water applied for agricultural irrigation. To assess the uncertainty associated with this water budget component, the model was recalibrated with 25 percent less areal recharge using PEST. This translates to about 3,000 afy of areal recharge to the basin on average.

Reducing recharge by this amount, without adjusting any other parameters, created numerical instability that prohibited obtaining meaningful results from PEST. In order to reduce this instability, the vertical to horizontal ratio of hydraulic conductivity was increased to 1:10 from 1:100. Similar to the previous scenario, there is very little difference in the hydrographs of observed and simulated water levels between the two calibrations (Figure 3-17). Calibration statistics also indicate that a very good calibration can be achieved with less recharge in the system (Figure 3-18). Transmissivity changed significantly (Figure 3-19) although the range of values for transmissivity remains consistent with observed specific capacity data for the basin and the final calibration transmissivity distribution.

Because the model is equally well calibrated with 25 percent less recharge, groundwater discharge to creeks was used to assess the impact of altering the recharge while maintaining a well calibrated model. Figure 3-20 shows groundwater discharge to Llagas Creek, Uvas Creek, and Pajaro River for both calibrations. Under alternative calibration, less groundwater discharges to the creeks. This may be due to less overall recharge or the increase in the ratio of vertical to horizontal hydraulic conductivity to 1:10, or some combination of the two. As discussed below in Section 3.4, Recommendations, there are no paired gage data from the creeks to assess which calibration is more reasonable. Detailed data collected from paired stream gages at multiple locations along the creeks may be used to quantify the amount and timing of groundwater discharge to the creeks.

3.4 Recommendations

Development and calibration of a numerical model provides useful insight into areas of the underlying conceptual model that require additional data, and often sheds light onto physical processes occurring in the basin that were not previously understood. Following model development, calibration, and uncertainty analysis, a number of data gaps were identified for the Llagas Basin. Addressing these data gaps will improve the conceptual understanding of the basin, lead to a better model calibration, and provide a more robust predictive tool for managing this groundwater resource from both a quantity and quality perspective. Based on the recent modeling effort it is recommended that the District complete the following tasks:

1. **Install monitoring well clusters at select locations in the basin.** Vertical gradients play an important role in contaminant migration and intentional recharge operations in the basin. The current model calibration relied on water level data from 40 monitoring wells. Construction data were available for only five of these wells and they were constructed with relatively long screen intervals (100 to 600 feet). Therefore, vertical gradients may not be accurately represented in the current version of the model. In the absence of any meaningful depth-discrete water level data, vertical gradients can not be evaluated and their impact on local and/or regional groundwater flow can not be assessed. Accordingly, it is recommended that at least four monitoring well clusters be installed at strategic locations in the basin. Each monitoring well cluster should consist of as many as three or four individual monitoring points with relatively short screen intervals (10 to 20 feet) completed in zones identified from borehole geophysics. These cluster wells should be monitored at frequent intervals throughout the year so that seasonal changes in the vertical gradients in the basin can be identified.
2. **Install and collect stream stage and flow data from paired gages on Llagas Creek, Uvas Creek, and the Pajaro River.** The District desires to use the model to evaluate current and future intentional recharge practices. Though the current model version uses the River (RIV) package as a source of groundwater discharge, adequate observed streamflow and stage data were not available to be used as a calibration target. In addition, there were no data available on whether the creeks act as a source of groundwater recharge to the basin. Accordingly, gage data should be collected from multiple stream reaches on a regular basis to help quantify the volume and timing of water being recharged to or discharged from the groundwater system in any given location along the streams. Data collected from stream gages may be used with MODFLOW's Stream Routing Package (STR1) or RIV package to simulate these fluxes

and provide a calibration target for the water budget. In addition, several monitoring wells should be installed near key locations near the streams to directly measure the changes in groundwater levels that are caused by changes in stream stage. Data from these wells can be used to quantify the properties of the streambed and aquifer near the stream.

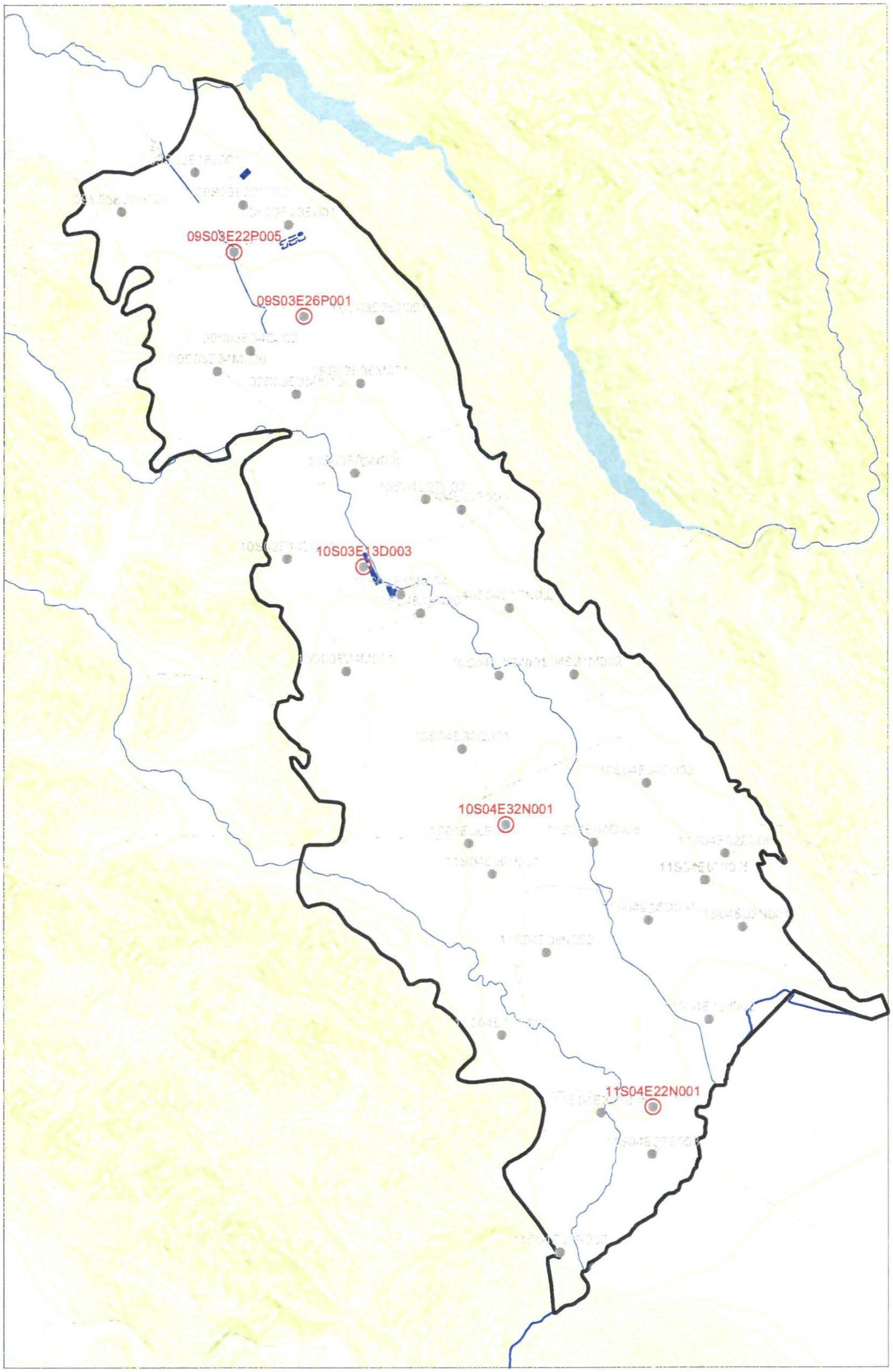
3. **Acquire and update land use data for the basin on an annual or semi-annual basis.** On average, deep percolation from precipitation, water applied for agricultural irrigation, water applied for landscape irrigation, and urban recharge account for over 25 percent of the basin's recharge but can be as high as 65 percent during winter stress periods. Each of these water budget components is directly influenced by land use in the basin. As land use changes over time the rates and distribution of recharge will also need to change. In the absence of accurate land use data a significant amount of uncertainty will lie in simulation of these water budget components. Accordingly, it is recommended that land use data be collected on at least an annual basis and maintained electronically in a GIS or equivalent. At a minimum, the GIS database should, maintain information on location, size of area, and type of land use. One suggested method for regularly updating land use data is to "calibrate" an aerial photograph to a land use map developed by the DWR for a similar time period. Land use types may then be more easily identified in future aerial photographs, which can be efficiently digitized and the information loaded into the GIS.

4. **Perform aquifer tests on existing production wells.** Aquifer test data are not available for existing production wells in the basin. Transmissivity was estimated from available specific capacity data. Specific capacity calculated from driller's logs was used as a target for the northern and central portions of the basin. More reliable specific capacity data from the City of Gilroy were used to estimate transmissivity of the southern basin (City of Gilroy to the Pajaro River). The Cities of Gilroy and Morgan Hill operate a number of high-capacity production wells suitable for aquifer testing. Aquifer test data from production wells in these areas would provide a better estimate and calibration target for aquifer properties. Accordingly, it is recommended that suitable production wells be identified and aquifer tests performed on these wells. In addition, one-hour efficiency tests should be conducted on suitable municipal and agricultural wells to obtain additional specific capacity data. Priority should be given to testing wells in the areas around San Martin and the City of Gilroy. Currently, aquifer test and reliable specific capacity information is not available in these general locations.

5. **Install and test as many as four test wells.** Very few data exist on vertical anisotropy (the ratio of vertical to horizontal hydraulic conductivity, K_v:K_h) in the basin. Vertical anisotropy is important to understanding vertical groundwater leakage. The rates and locations of vertical leakage may have a significant impact on groundwater flow. Currently, the model uses a K_v:K_h ratio of 1:100, but as demonstrated in the uncertainty analysis, the model may be calibrated with a ratio of 1:10. The difference may impact such predictions as discharge to and recharge from creeks and migration of perchlorate. To evaluate vertical anisotropy, it is recommended that as many as four test wells be installed near the monitoring well clusters outlined in the first recommendation. Each test well should be perforated in a discrete zone such that a screen from each well in the monitoring cluster is located adjacent to, below, and above the test well screen.

It is possible that testing of the existing pumping wells, coupled with data from the monitoring well clusters recommended above, could yield estimates of the vertical hydraulic conductivity of the Llagas Basin aquifers and aquitards. Therefore, prior to drilling new test wells, an evaluation of the use of existing wells to collect these data will be performed.

6. **Conduct a feasibility review for a water quality sampling program.** Water quality data collected on a consistent basis from depth-discrete (screen lengths less than 20 feet) monitoring wells are not available. Detailed water quality data may help manage the basin from a water quality perspective and more adequately identify groundwater flow patterns. It is recommended that a feasibility study be performed to evaluate the benefits of establishing a water quality monitoring program. The program should include collection of general water quality parameters as well as nitrate and boron from monitoring wells in the basin. Potential benefits of deuterium-oxygen and tritium isotopic sampling to assess origin, ages, and flowpaths of groundwater should also be evaluated. This is especially important since intentional recharge is a significant component of the basin's overall recharge.



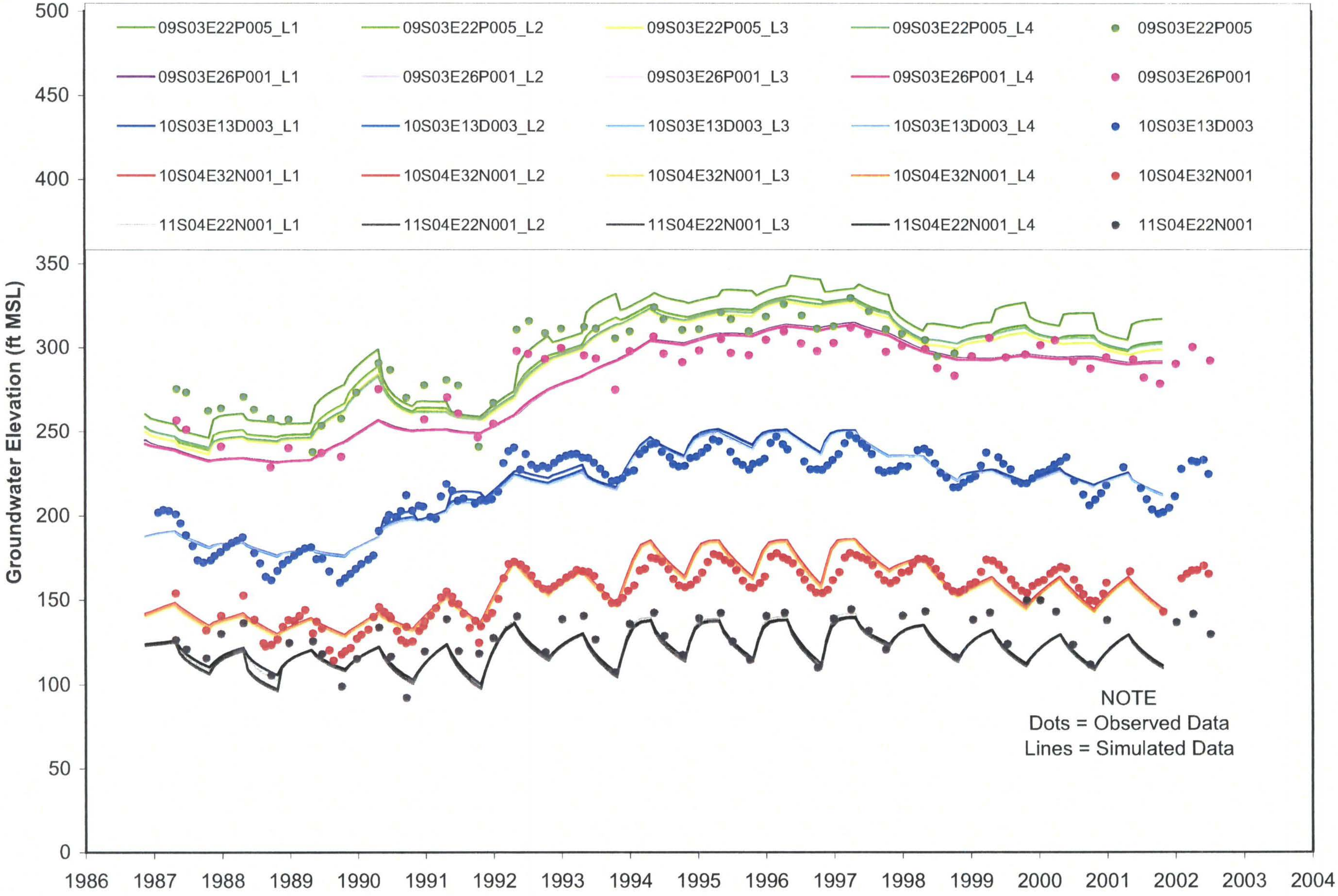
● Calibration Well

◎ Select Calibration Wells Discussed In Report

FIGURE 3-1
MONITORING WELLS USED DURING CALIBRATION

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

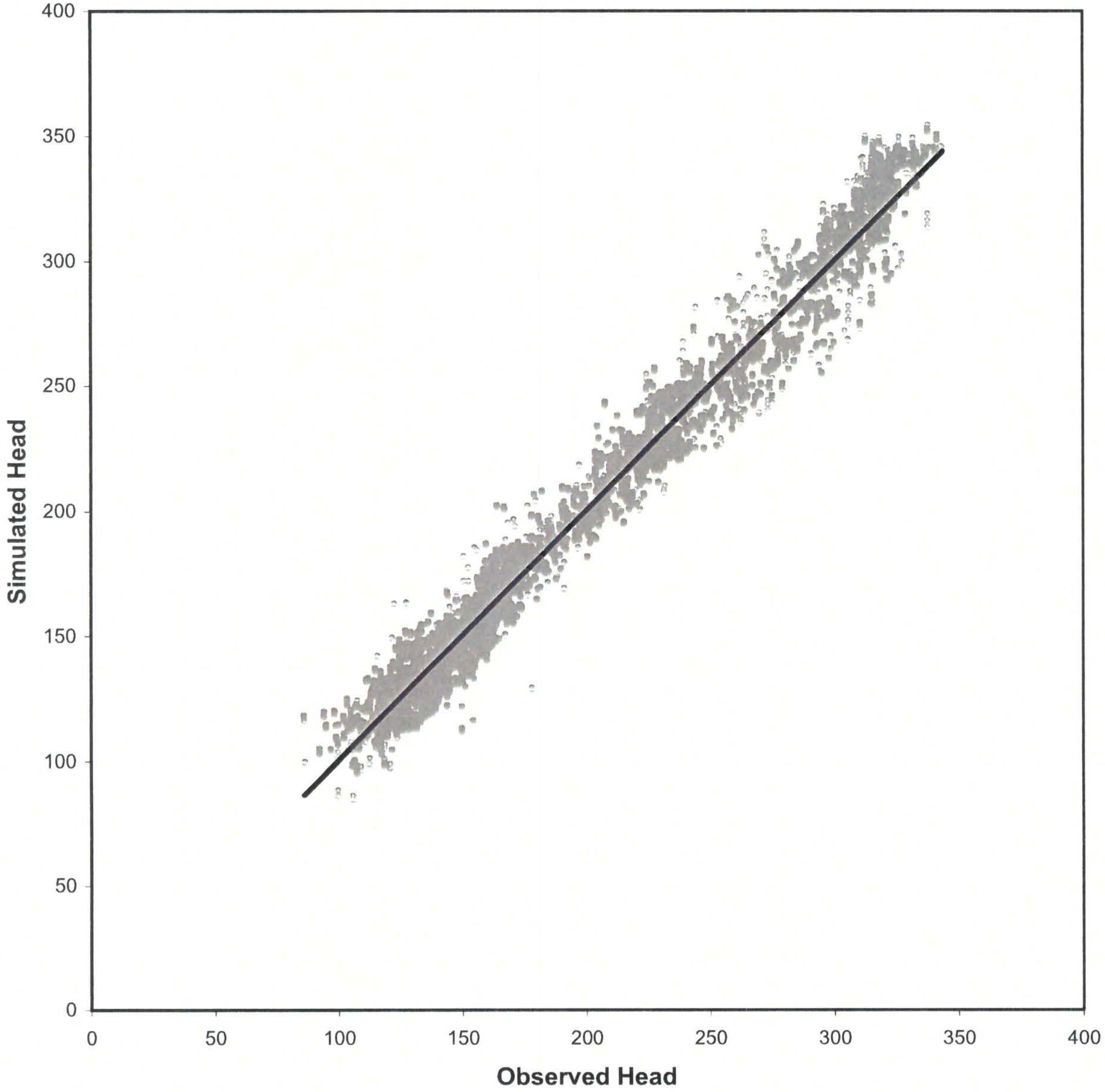
CH2MHILL



R133 Results.xls

FIGURE 3-2
CALIBRATION HYDROGRAPHS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



$R^2 = 0.9696$

RMS/Range = 4.4%

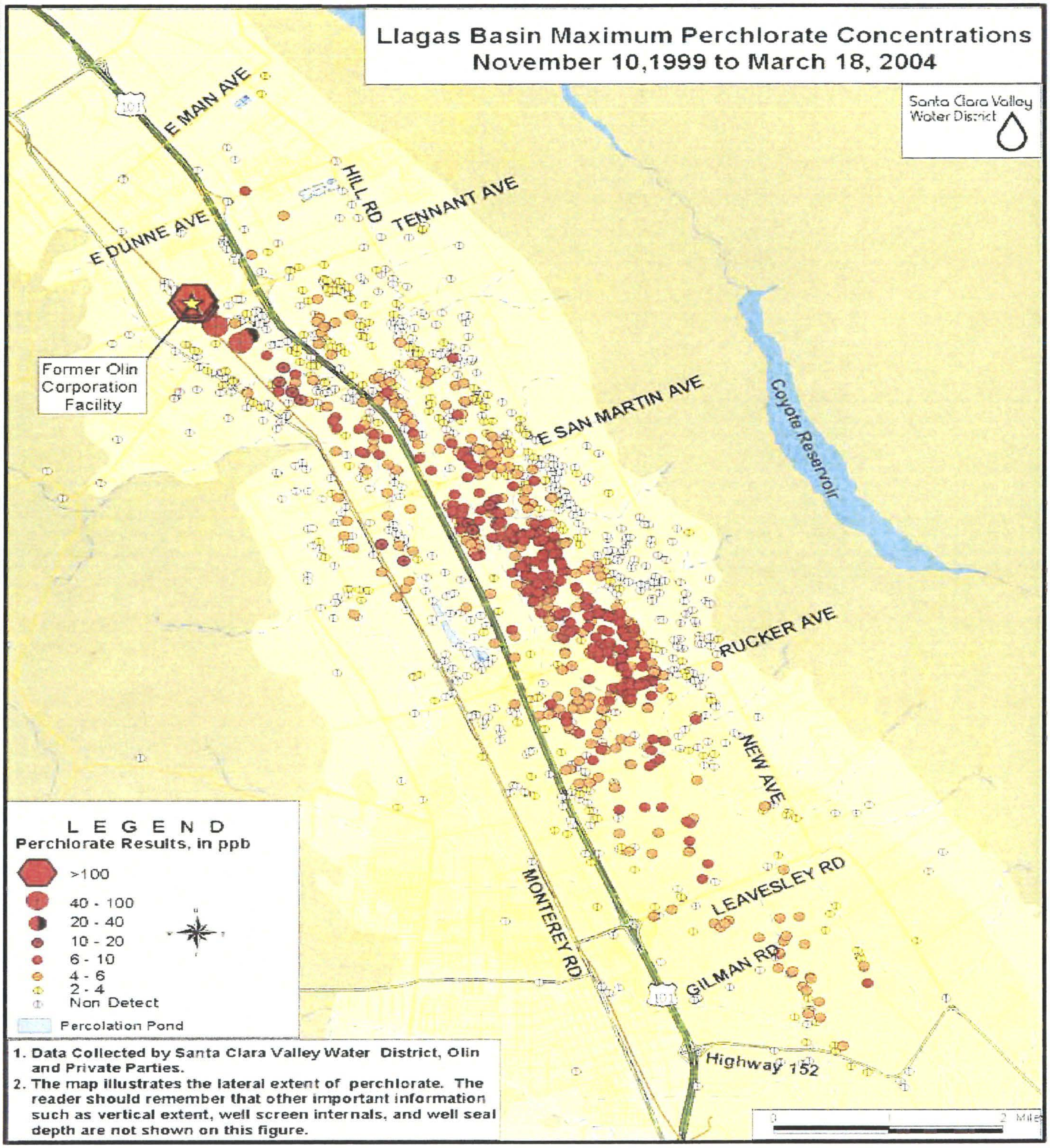
Residual Mean = -0.3

Absolute Residual Mean = 8.9

R133Stats.xls

FIGURE 3-3
RESIDUAL STATISTICS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



1. **Data Collected by Santa Clara Valley Water District, Olin and Private Parties.**
2. **The map illustrates the lateral extent of perchlorate. The reader should remember that other important information such as vertical extent, well screen internals, and well seal depth are not shown on this figure.**

FIGURE 3-4
LLAGAS BASIN MAXIMUM PERCHLORATE CONCENTRATIONS NOVEMBER 10, 1999 TO MARCH 18, 2004
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Source: SCVWD

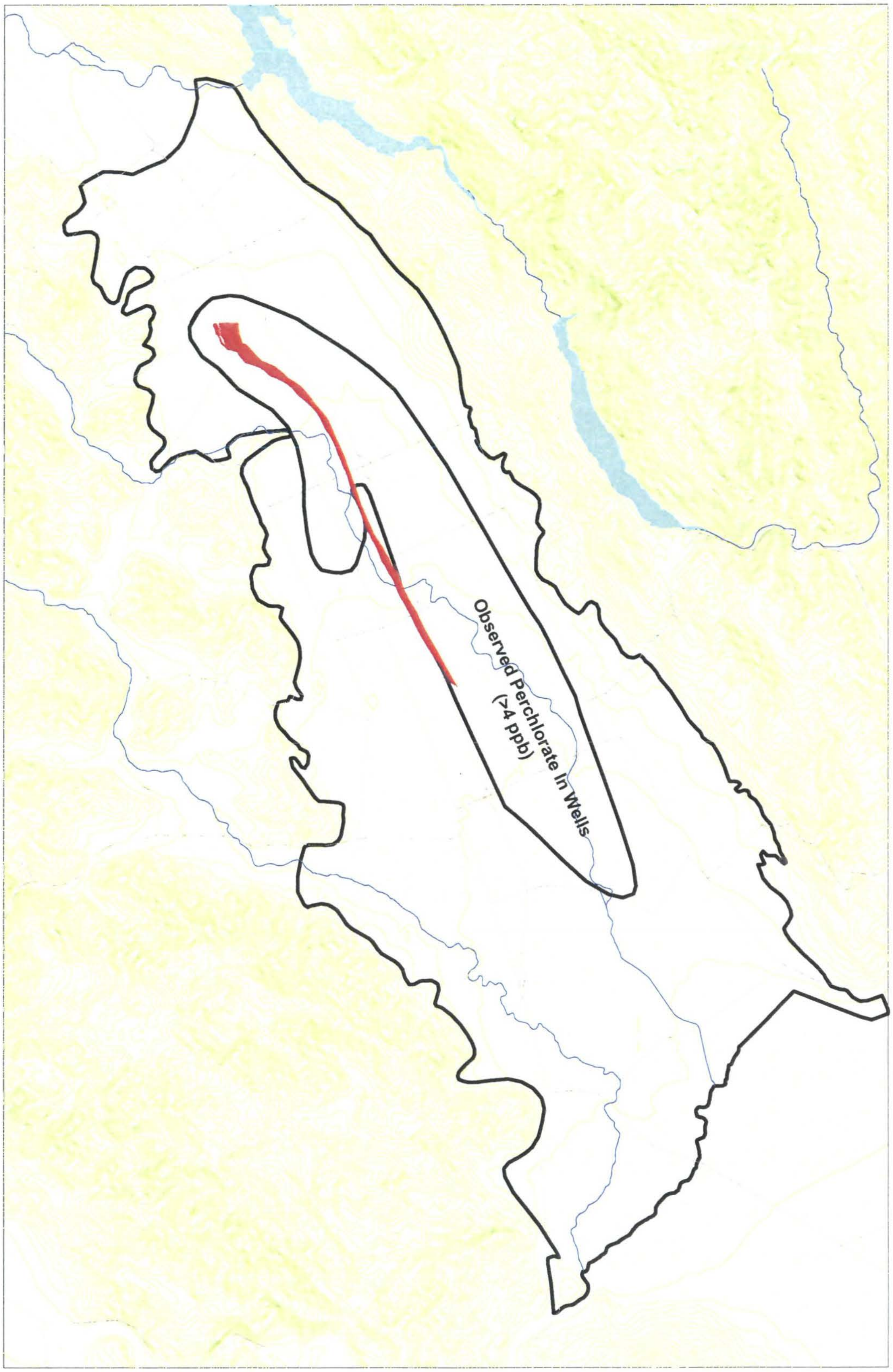
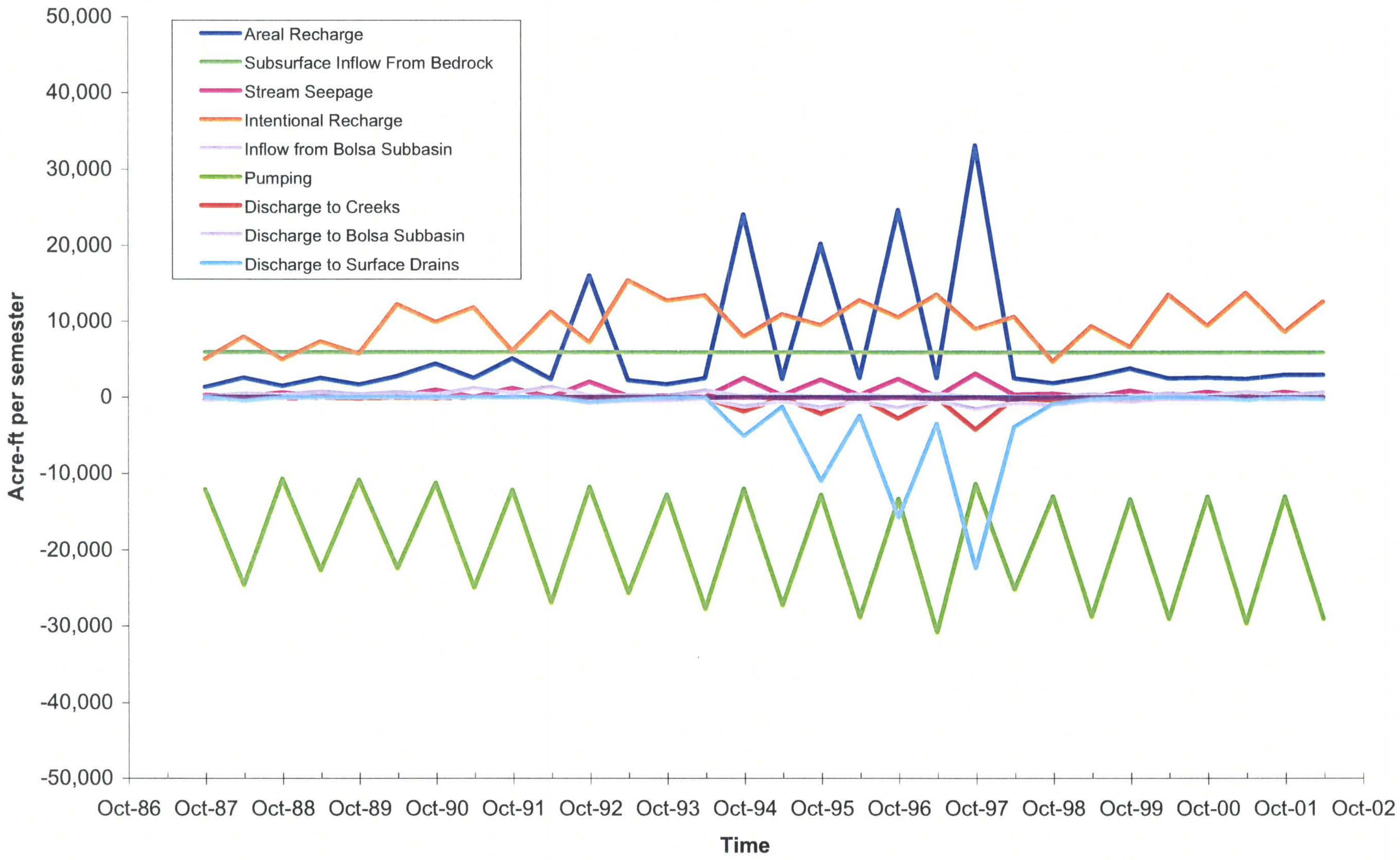


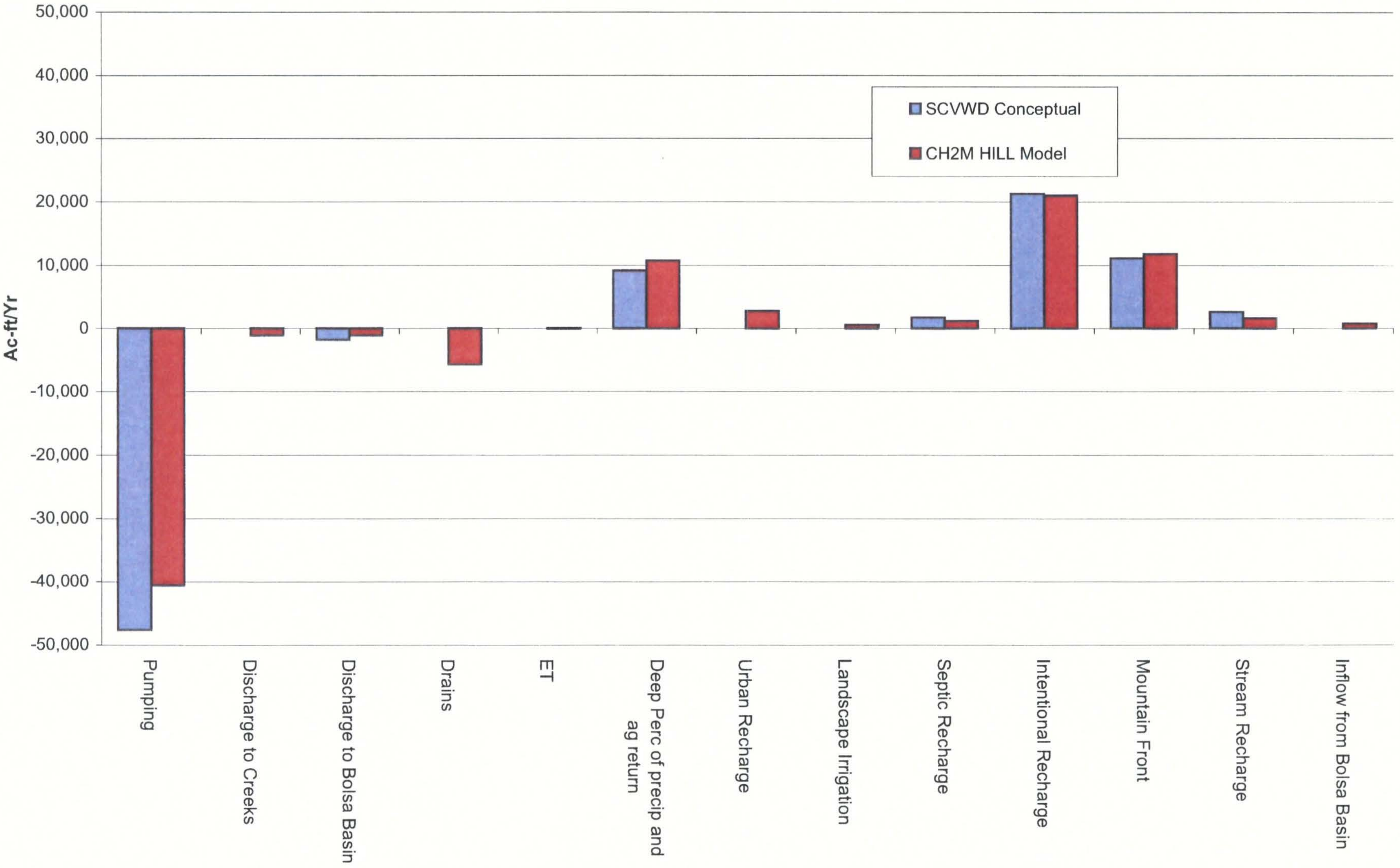
FIGURE 3-5
PARTICLE TRACKING
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT



R128_Budget.xls

FIGURE 3-6
SIMULATED WATER BUDGET COMPONENTS
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Average_WB_Analysis.xls

FIGURE 3-7
SCVWD DRAFT CONCEPTUAL WATER BUDGET AND AVERAGE SIMULATED WATER BUDGET (1990-2001)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

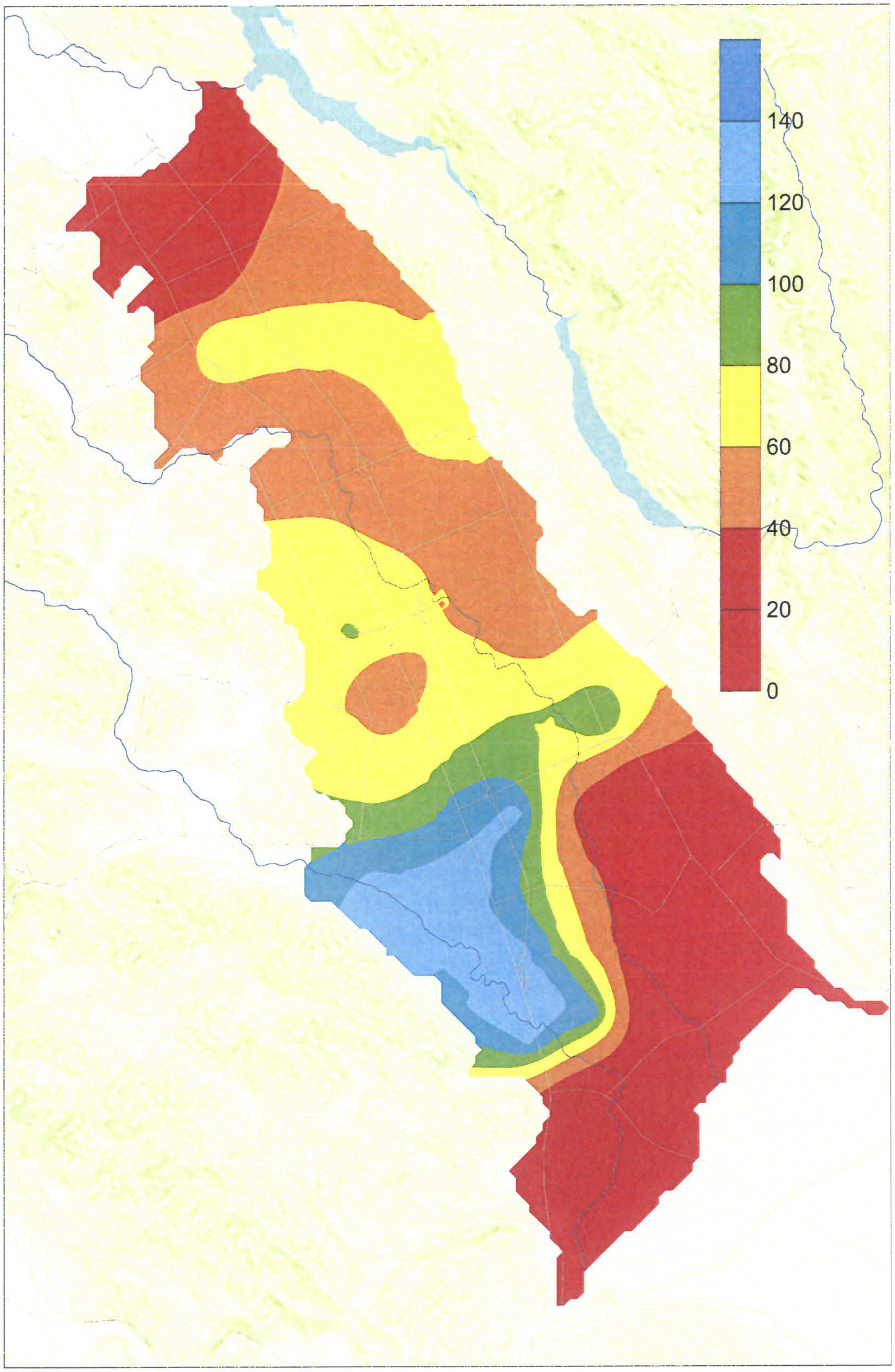


FIGURE 3-8
HYDRAULIC CONDUCTIVITY (ft/d)
LAYERS 1 THROUGH 4
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

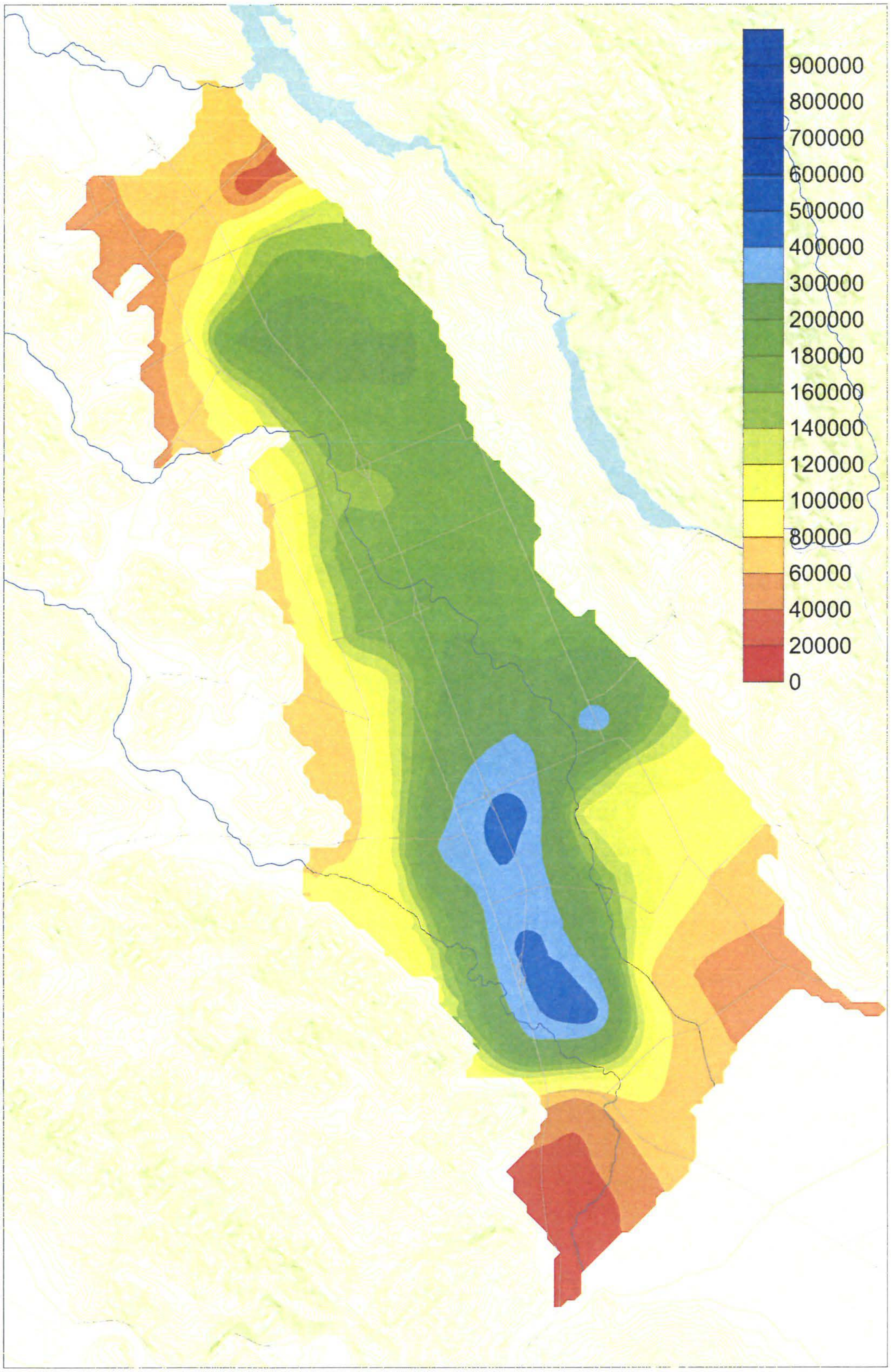


FIGURE 3-9
TRANSMISSIVITY DISTRIBUTION (gpd/ft)
FINAL CALIBRATION

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

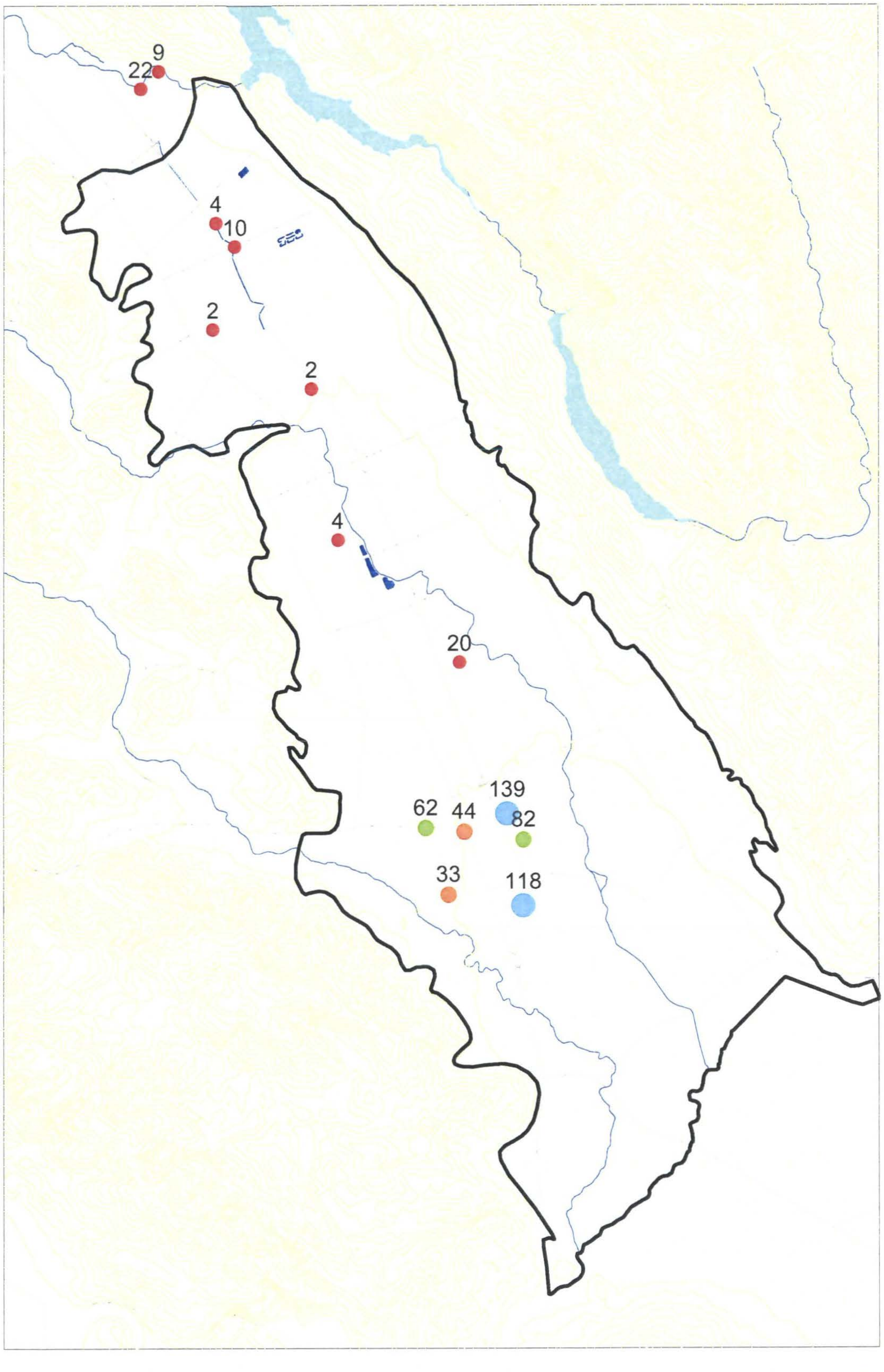


FIGURE 3-10
AVAILABLE SPECIFIC CAPACITY (gpd/ft)

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 3-10__5/13/05_ccc_sfo

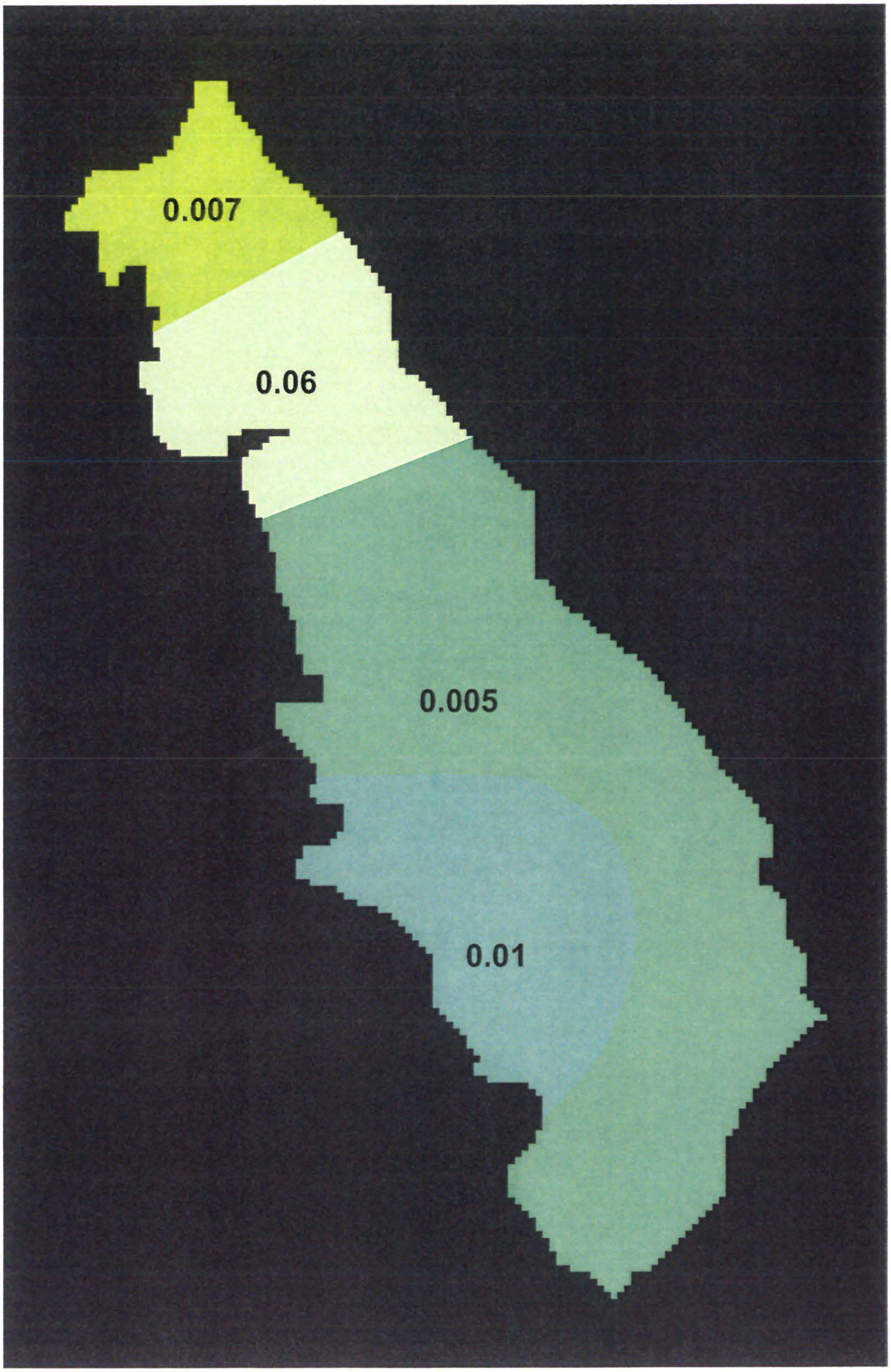
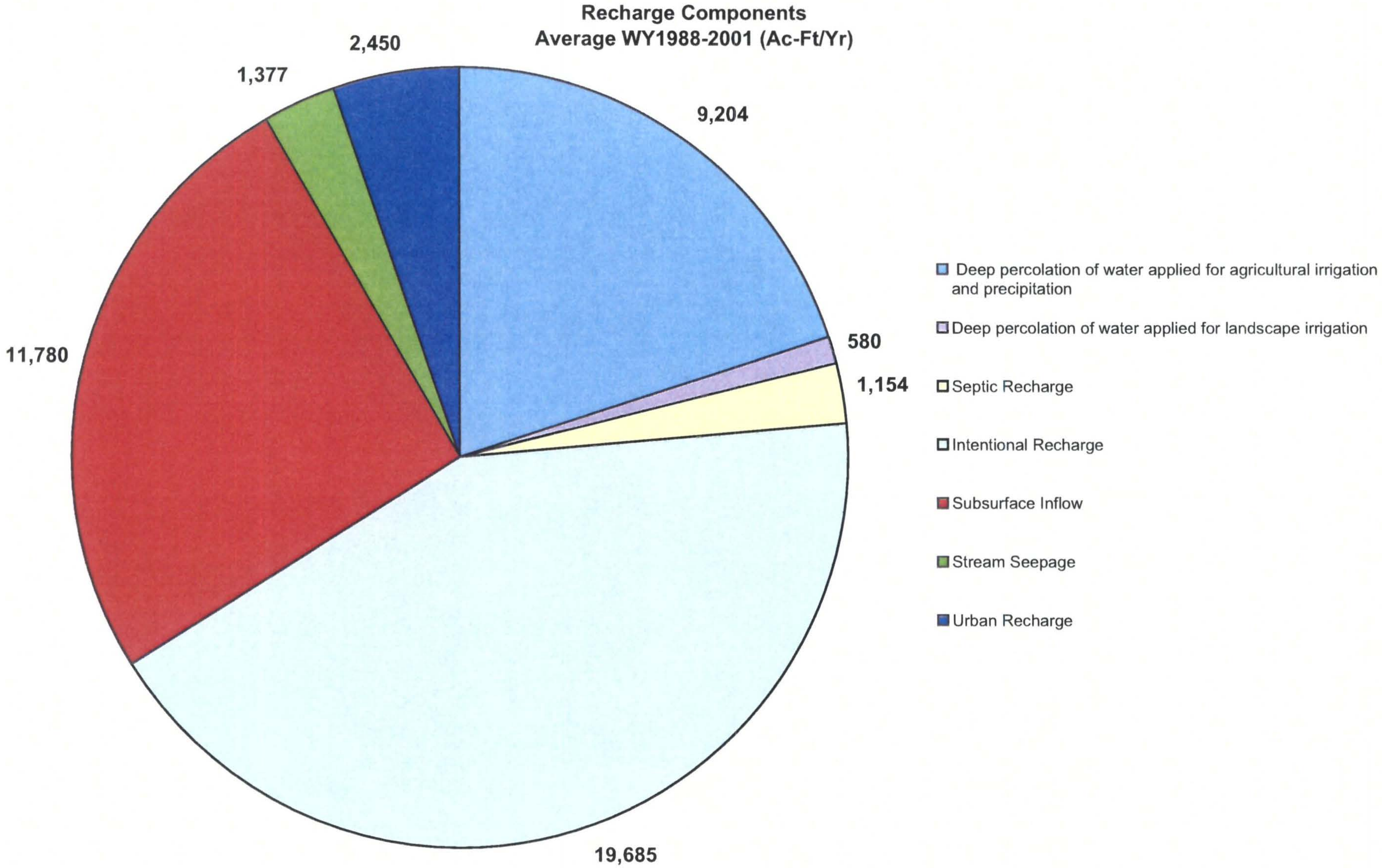


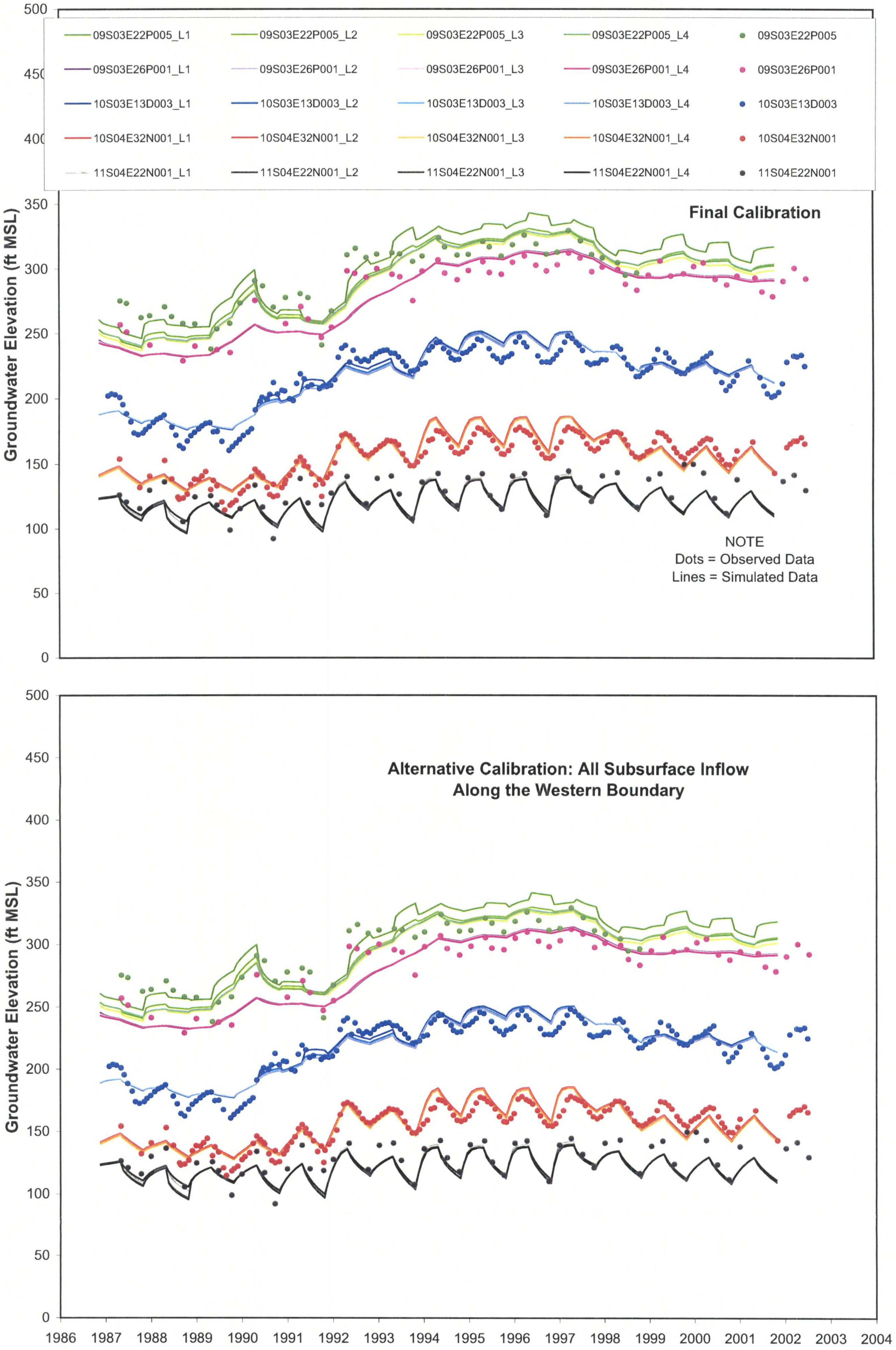
FIGURE 3-11
SPECIFIC YIELD DISTRIBUTION LAYER-1
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



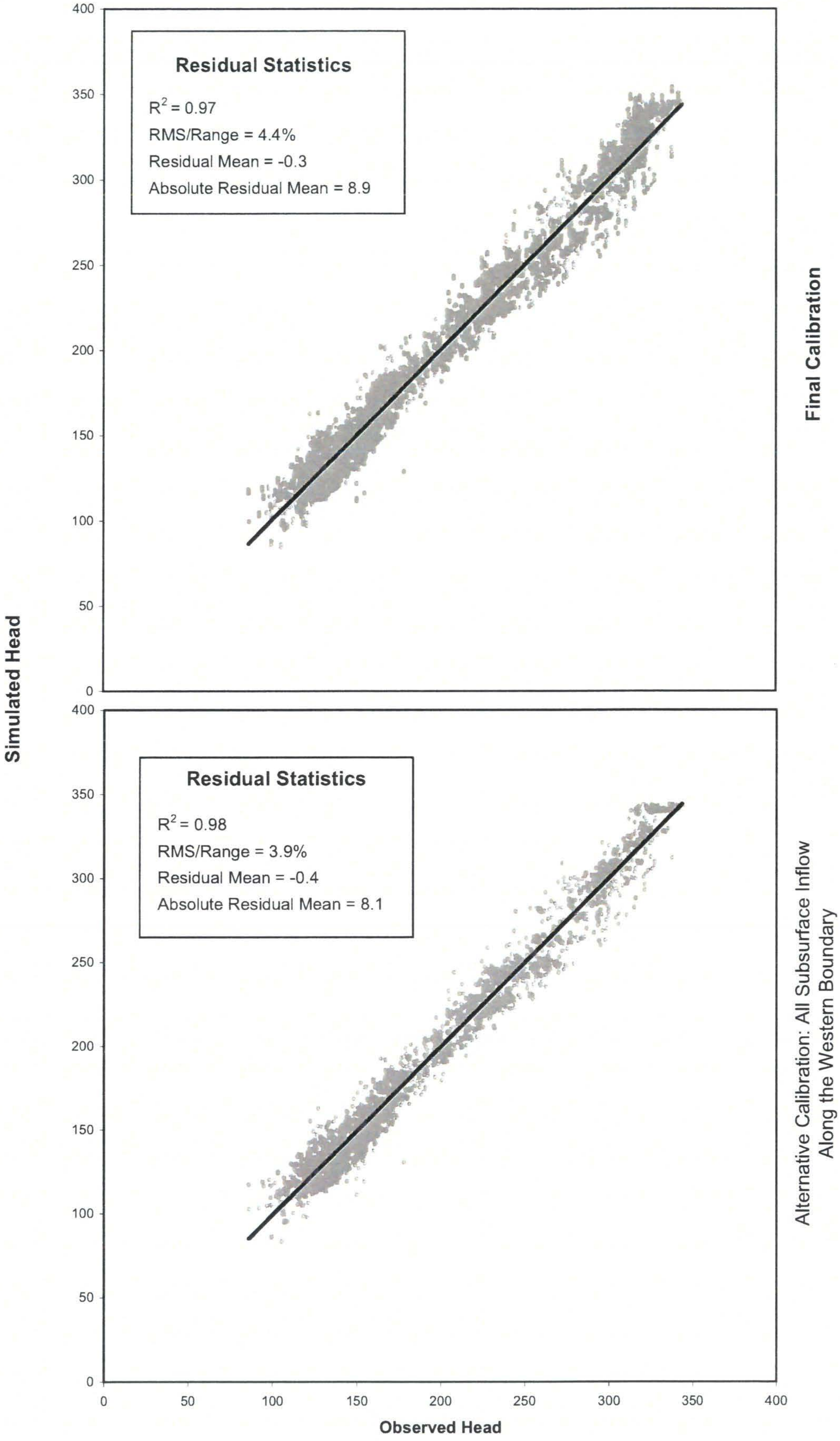
Average_WB_Analysis.xls

FIGURE 3-12
SIMULATED AVERAGE
RECHARGE DISTRIBUTION
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT



ComparisonFigsv2.xls

FIGURE 3-13
FINAL AND ALTERNATIVE CALIBRATION HYDROGRAPHS SCENARIO 1
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

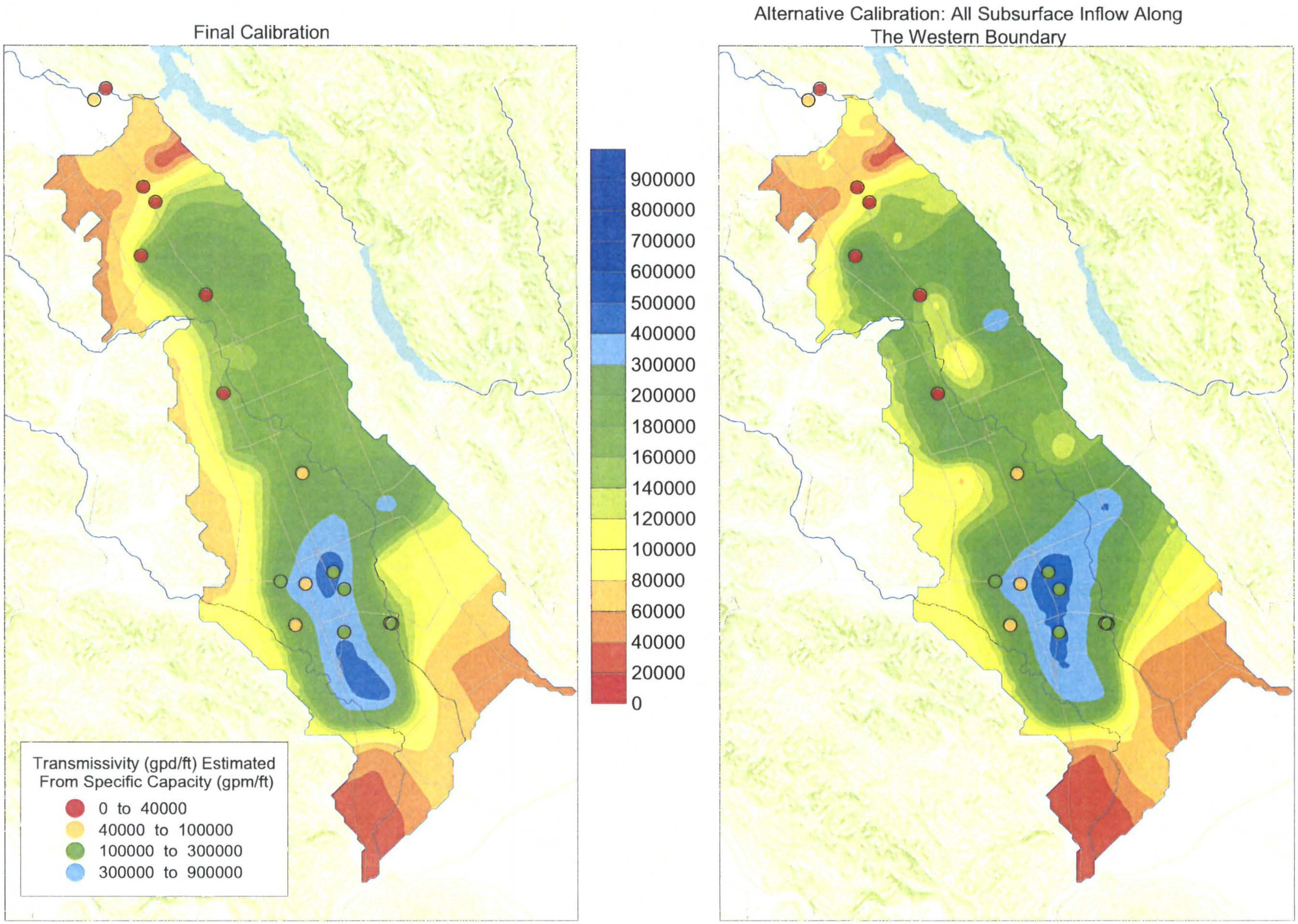


Final Calibration

Alternative Calibration: All Subsurface Inflow Along the Western Boundary

FIGURE 3-14
FINAL AND ALTERNATIVE RESIDUAL STATISTICS SCENARIO 1
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

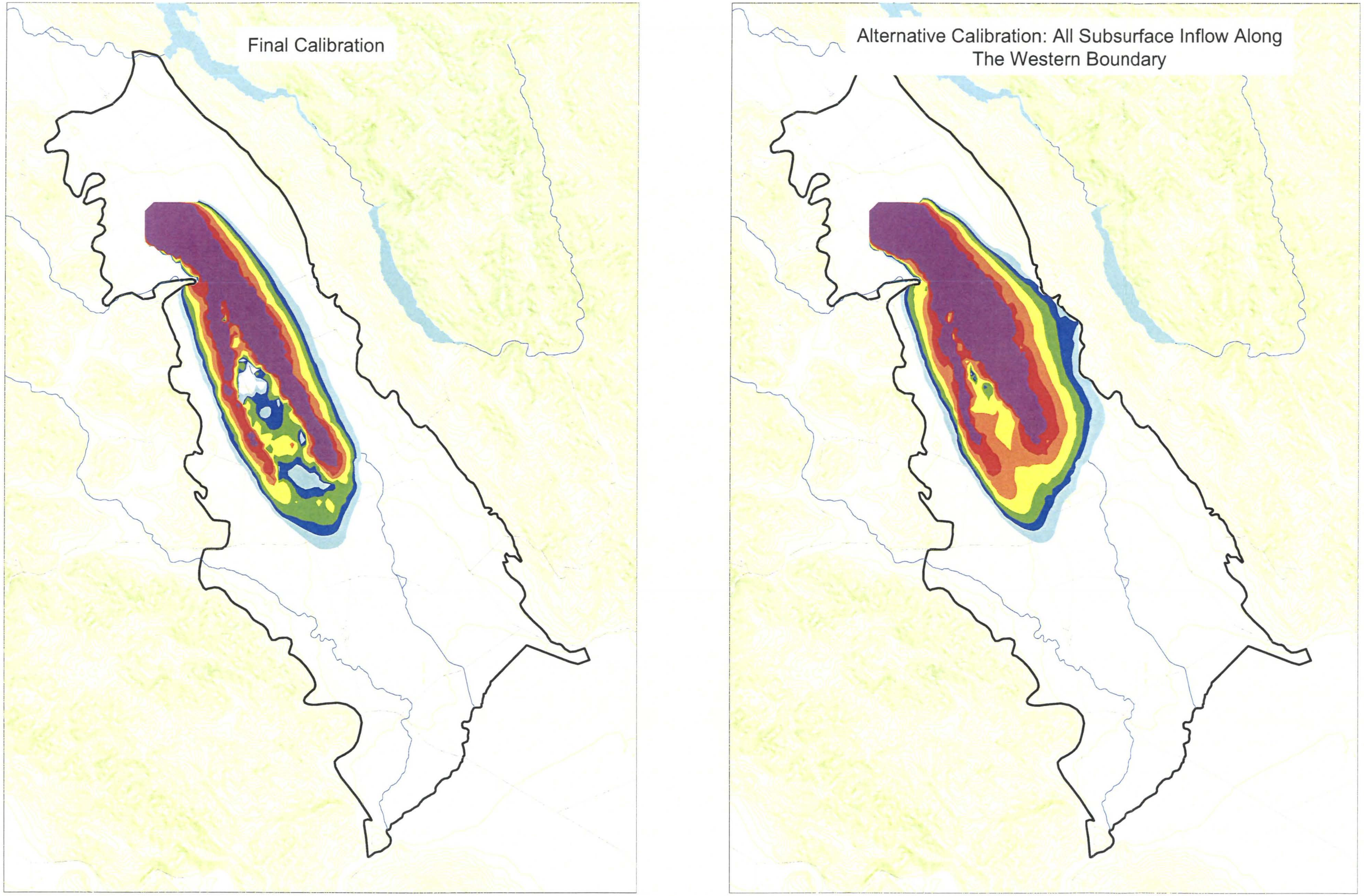

Final Calibration

Alternative Calibration: All Subsurface Inflow Along The Western Boundary

FIGURE 3-15
TRANSMISSIVITY DISTRIBUTION (gpd/ft)
FINAL AND ALTERNATIVE CALIBRATIONS (SCENARIO 1)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

188409.LB.05_Fig 3-15__5/24/05_ccc_sfo

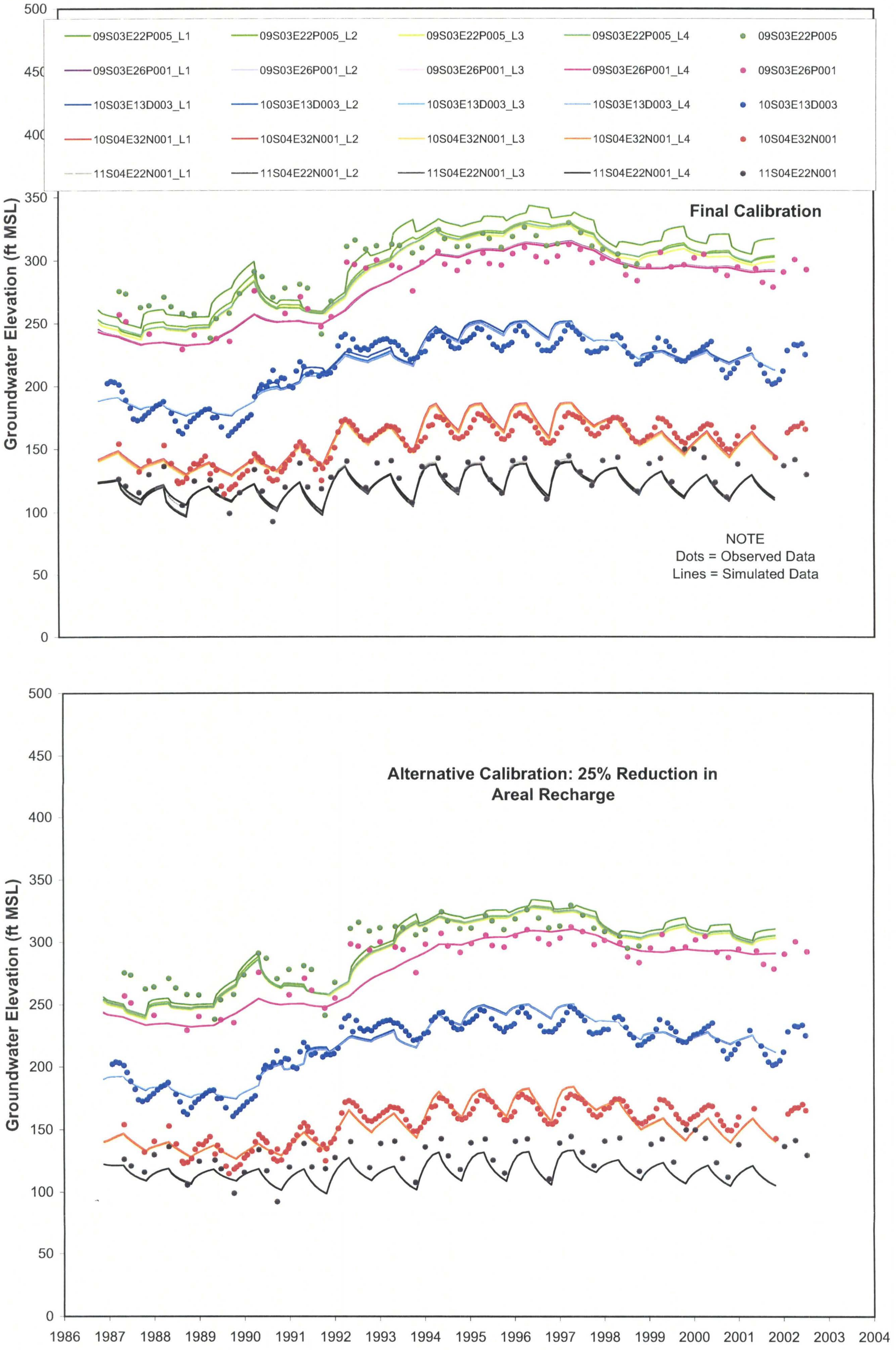


Final Calibration
Alternative Calibration: All Subsurface Inflow Along The Western Boundary

FIGURE 3-16
SIMULATION OF PERCHLORATE IN GROUNDWATER
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

188409.LB.05_Fig 3-16__5/13/05_ccc_sfo

CH2MHILL



ComparisonFigsv2.xls

FIGURE 3-17
FINAL AND ALTERNATIVE CALIBRATION HYDROGRAPHS SCENARIO 2
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

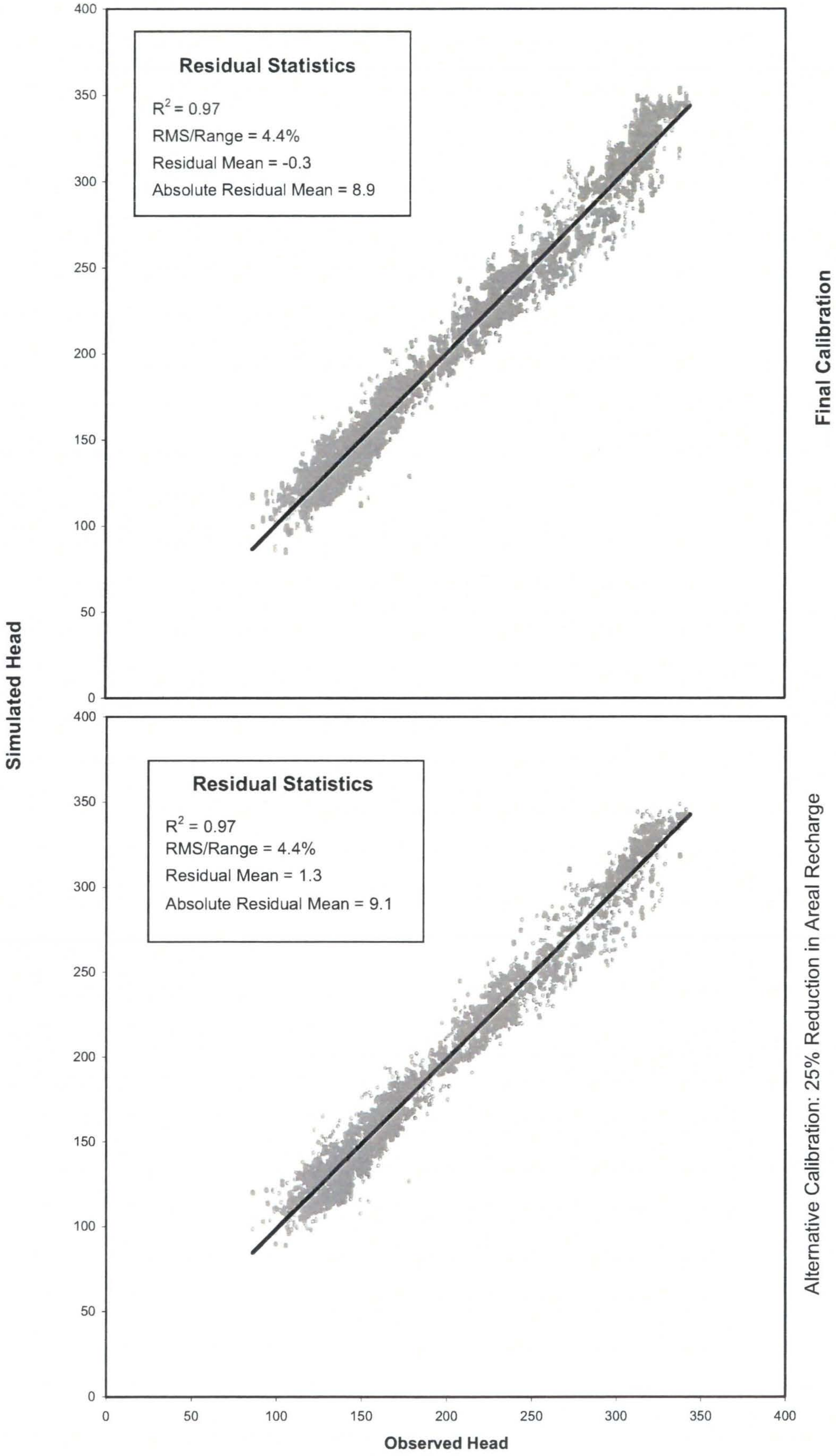


FIGURE 3-18
FINAL AND ALTERNATIVE RESIDUAL STATISTICS SCENARIO 2

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

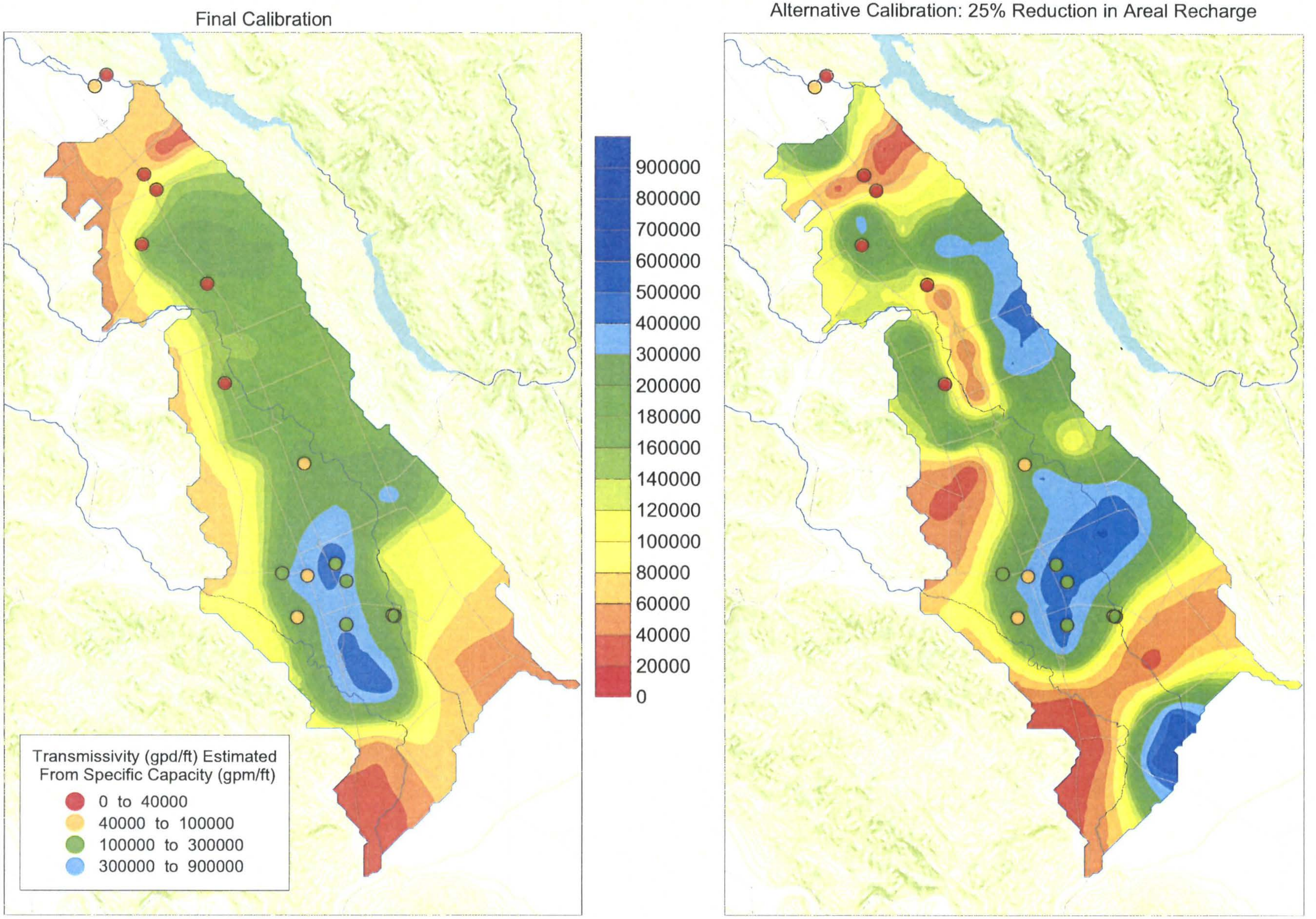
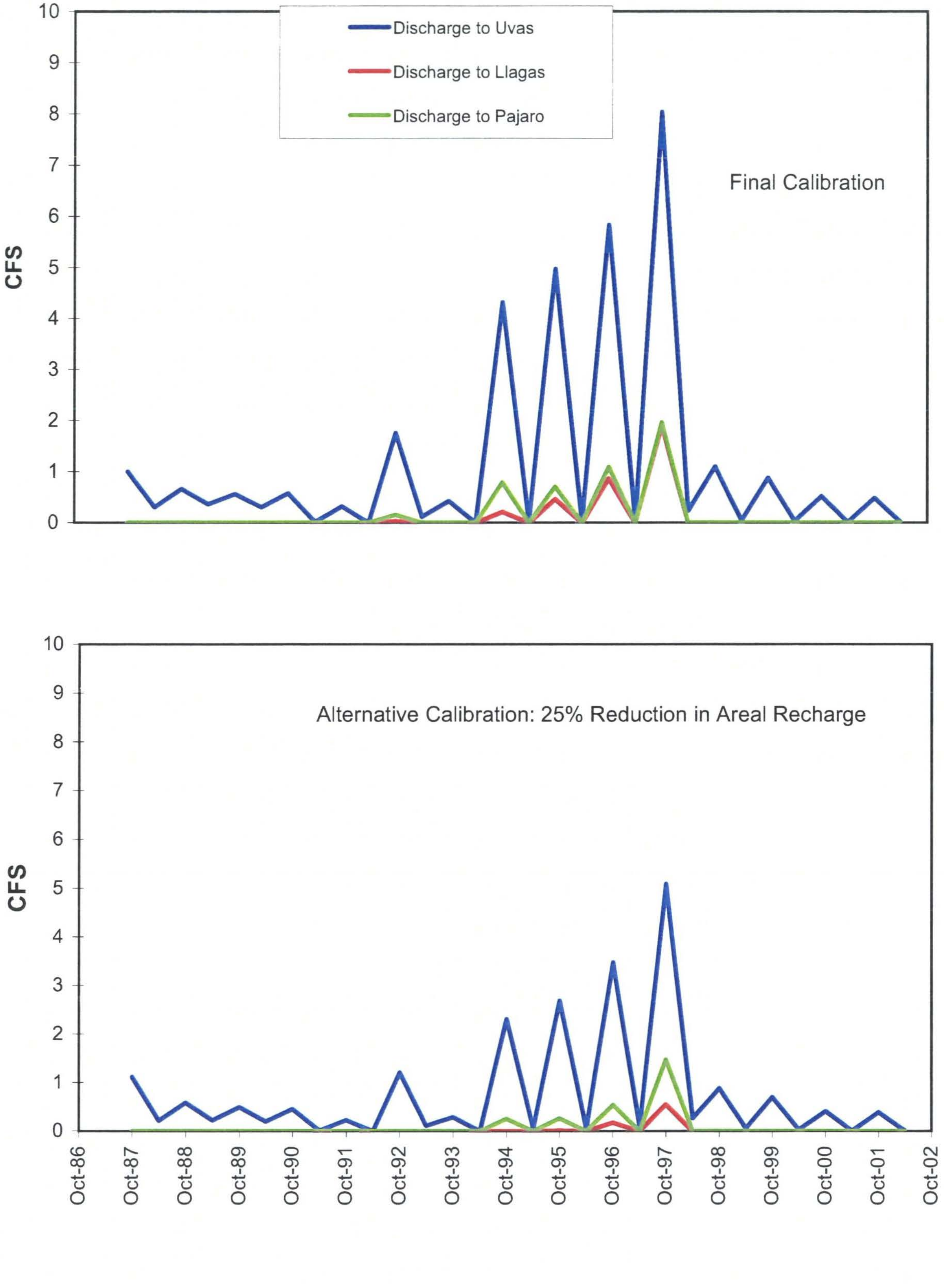


FIGURE 3-19
TRANSMISSIVITY DISTRIBUTION (gpd/ft)
FINAL AND ALTERNATIVE CALIBRATIONS (SCENARIO 2)
LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL



Creek Comparison.xls

FIGURE 3-20
DISCHARGE TO CREEKS FINAL AND ALTERNATIVE CALIBRATIONS

LLAGAS BASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

CH2MHILL

SECTION 4

4.0 References

Abuye, Chanie W. 2003. *Llagas Subbasin Conceptual Hydrogeologic Model Draft Summary*. Santa Clara Valley Water District. September 2003.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56, Rome.

Anderson, Mary P., and W.W. Woessner. 1992. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*. Academic Press. P. 70.

Blaney, H.F., P.R. Nixon, G.P. Lawless, and E.J. Wiedmann. 1963. *Utilization of the Water of the Santa Ynez River Basin for Agriculture in Southern Santa Barbara County, California*. United States Department of Agriculture, Agricultural Research Service, Soil and Water Conservation Research Division, Southwest Branch. October.

California Department of Water Resources (DWR). 1981. *Evaluation of Groundwater Resources, South San Francisco Bay, Vol. IV: South Santa Clara County Area*. Bulletin 118-1. May 1981.

California Department of Water Resources (DWR). 1990. Llagas Valley Land Use Survey.

CH2M HILL. 2000. *Coyote Valley Groundwater Report for Metcalf Energy Center*. Prepared for the California Energy Commission. July 2000.

CH2M HILL. 2004a. *Llagas Basin Conceptual Model Review (Draft)*. Prepared for Santa Clara Valley Water District. April 2004.

CH2M HILL. 2004b. *Development of the Llagas Numerical Model (Draft)*. Prepared for Santa Clara Valley Water District. June 2004.

CH2M HILL, 2005. *Llagas Numerical Model Calibration.(Draft)*. Prepared for Santa Clara Valley Water District. February 2005.

Driscoll, F.G. 1995. *Groundwater and Wells*. Second Edition. St. Paul, MN: Johnson Screens.

Hoose, Seena Nicolaisen. 1986. *Was There a Great Pleistocene Lake San Benito?* Thesis prepared to the Faculty of the Department of Geology, San Jose State University. December 1986.

Iwamura, T. and L.D. Wilson. 1989. *Standards for the Construction and Destruction of Wells and other Deep Excavations in Santa Clara County*. Santa Clara County Water District. June.

McCloskey, T.F. and E.J. Finnemore. 1996. "Estimating Hydraulic Conductivities in an Alluvial Basin from Sediment Facies Models." *Groundwater* Vol. 34, No. 6, pp. 1024-1032.

Santa Clara Valley Water District (SCVWD). 2004. Personal communication with Greg Meamber/SCVWD. June.

Turner, Kenneth M. 1991. *Annual Evapotranspiration of Native Vegetation in a Mediterranean-Type Climate.* Water Resources Bulletin, American Water Resources Association. February 1991.

U.S. Department of Agriculture (USDA). 1974. *Soil Survey of Eastern Santa Clara Area, California.*

Zheng, Chunmiao and Bennett, G.D. 1995. *Applied Contaminant Transport Modeling: Theory and Practice.* San Francisco: Van Nostrand Reinhold.

APPENDIX A

Appendix A
Pumping Well Database and Algorithm

APPENDIX A

Pumping Well Database and Algorithm

Available pumping well locations, rates, construction details, and lithology for wells in the Llagas Basin were provided by the District in electronic format. Data consisted of 2,913 pumping wells of which only 213 had screen or depth information. Wells with screen data accounted for 21 percent of the pumpage in the basin (Table A-1 and Figures A-1 through A-2). Only municipal and agricultural wells are presented in these figures because they comprise the majority of the pumping in Llagas Basin. Based on these charts a target list of about 300 wells was developed where screen and/or total depth information would advance our understanding of vertical distribution of pumpage in the basin. The District obtained some of the logs for these wells. A total of 45 additional paper logs were obtained and entered in the electronic database. After updating the database, wells with screen data account for about 36 percent of the pumping in the basin (Figures A-3 through A-4).

Remaining wells without construction information were assigned screen elevations using an algorithm that relies on existing screen data for wells in the Llagas Basin. Pumping wells in the Llagas Basin were subdivided based on water use (i.e., municipal and industrial, agricultural, domestic, and non-pumping). Municipal and agricultural wells were further subdivided based on the average non-zero pumping rate for a given well, and whether they were pumped more or less than 50 afy. Domestic wells in Llagas Basin do not pump more than 50 afy and NP wells with screen data are too few to warrant subdividing by pumpage, so this distinction was not made for these classes of wells.

Within each of the pumping well categories, top and bottom screen elevation surfaces were developed by spatially interpolating known pumping well screen elevations across the basin. Wells with screen data used to create the surfaces are plotted on the attached maps as black dots. The screen intervals for these wells are also represented graphically in attached charts. Grey dots represent wells without construction information. Red dots represent outliers that fall within the particular category but were not used in interpolation since these screen elevations are anomalous. Wells without construction data were then assigned top and bottom screen elevations based on interpolation using a kriging algorithm. Screen intervals assigned to pumping wells are represented graphically on the attached graphs. Well locations are illustrated on these graphs along the x-axis from north (left) to south (right).

	All Wells		Wells with Screen Data (Original Dataset)			Wells with Screen Data (Updated Dataset)		
Type of Pumping	**Count**	**Pumping (AF)**	**Count**	**Pumping (AF)**	**% of total pumping by type**	**Count**	**Pumping (AF)**	**% of total pumping by type**
MU	179	184,698	28	86,403	46.8%	36	122,566	66.4%
DO	2,009	44,196	146	1,120	2.5%	147	2,221	5.0%
AG	434	242,127	18	9,375	3.9%	51	43,862	18.1%
NP	291	42,083	21	11,816	28.1%	24	17,176	40.8%
Total	**2,913**	**513,105**	**213**	**108,714**	**21.2%**	**258**	**185,825**	**36.2%**

TABLE A-1
SUMMARY OF WELLS IN DATABASE

LLAGAS SUBBASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Pumping_Screen_Analysis.xls -- PumpingSummary_Old vs New -- 04/15/2004

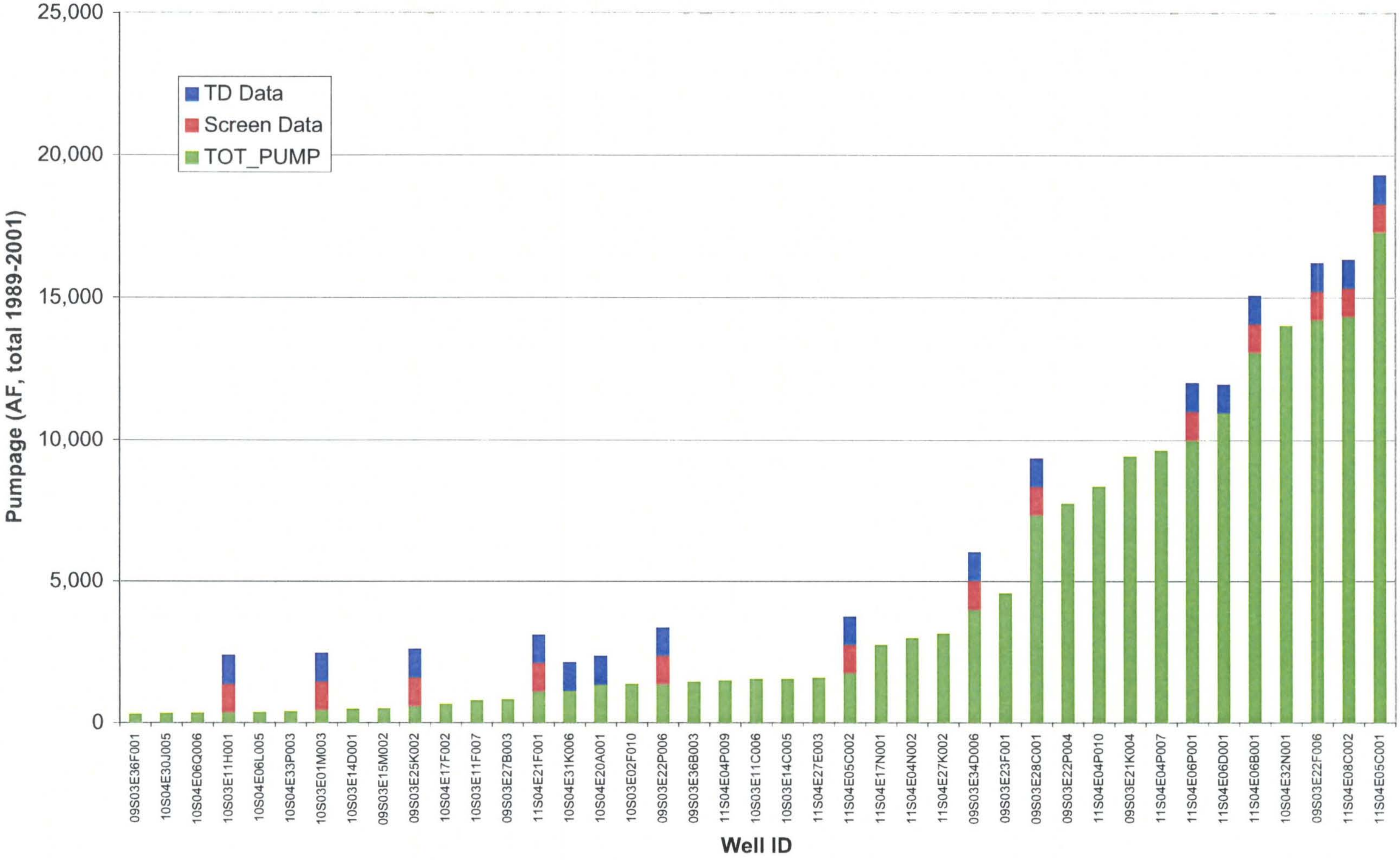


FIGURE A-1
MUNICIPAL WELLS WITH AND WITHOUT
SCREEN DATA (>250 AFY)
LLAGAS SUBBASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Pumping_Screen_Analysis_OriginalDataset.xls -- C-MU_BigPumpers (2) -- 04/15/2004

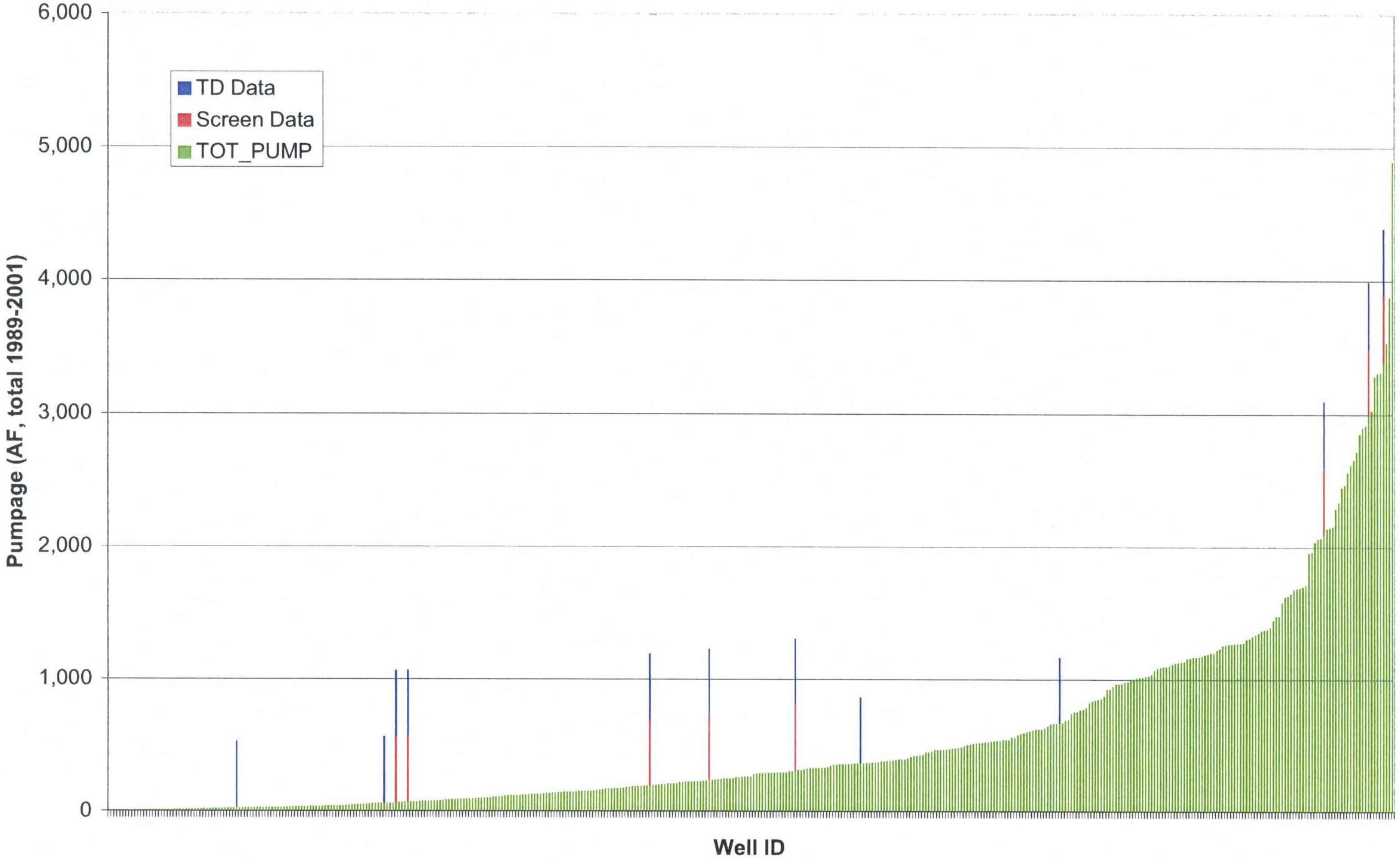


FIGURE A-2
AG WELLS WITH AND WITHOUT SCREEN DATA

LLAGAS SUBBASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Pumping_Screen_Analysis_OriginalDataset.xls -- C-AG (2) -- 04/15/2004

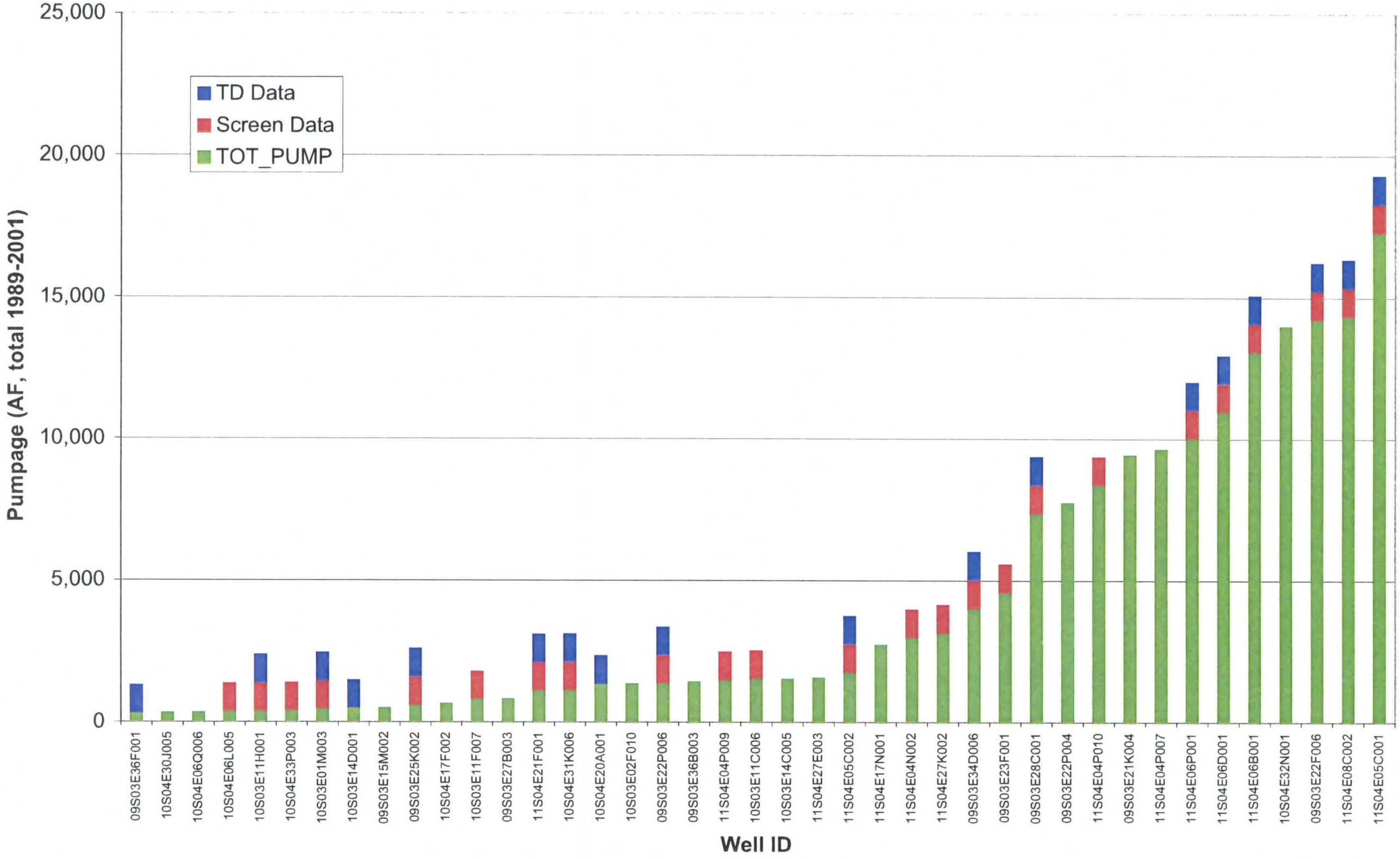


FIGURE A-3
MUNICIPAL WELLS WITH AND WITHOUT
SCREEN DATA (>250 AFY) AFTER DATABASE UPDATE
LLAGAS SUBBASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Pumping_Screen_Analysis.xls -- C-MU_BigPumpers (2) -- 04/15/2004

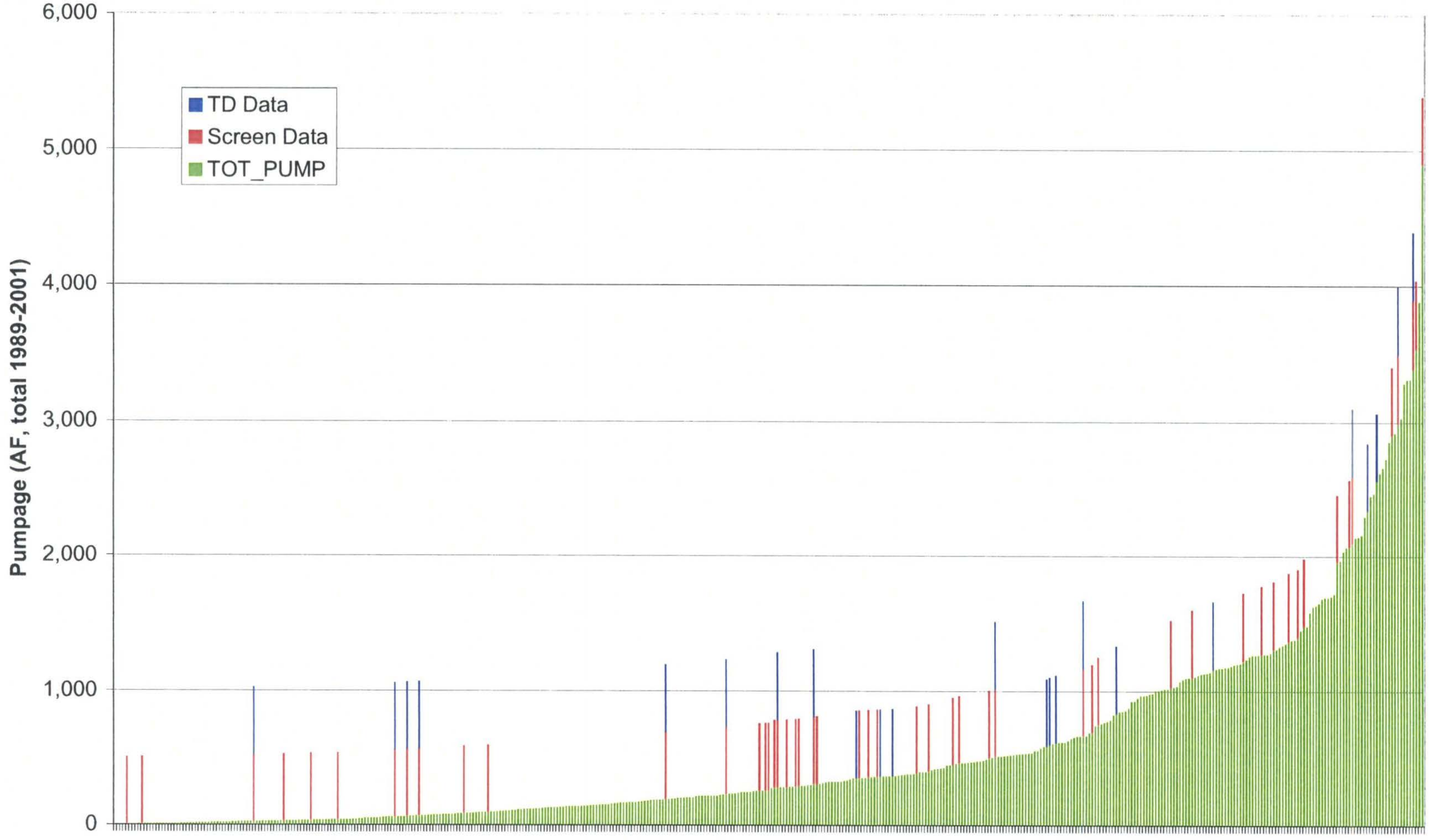
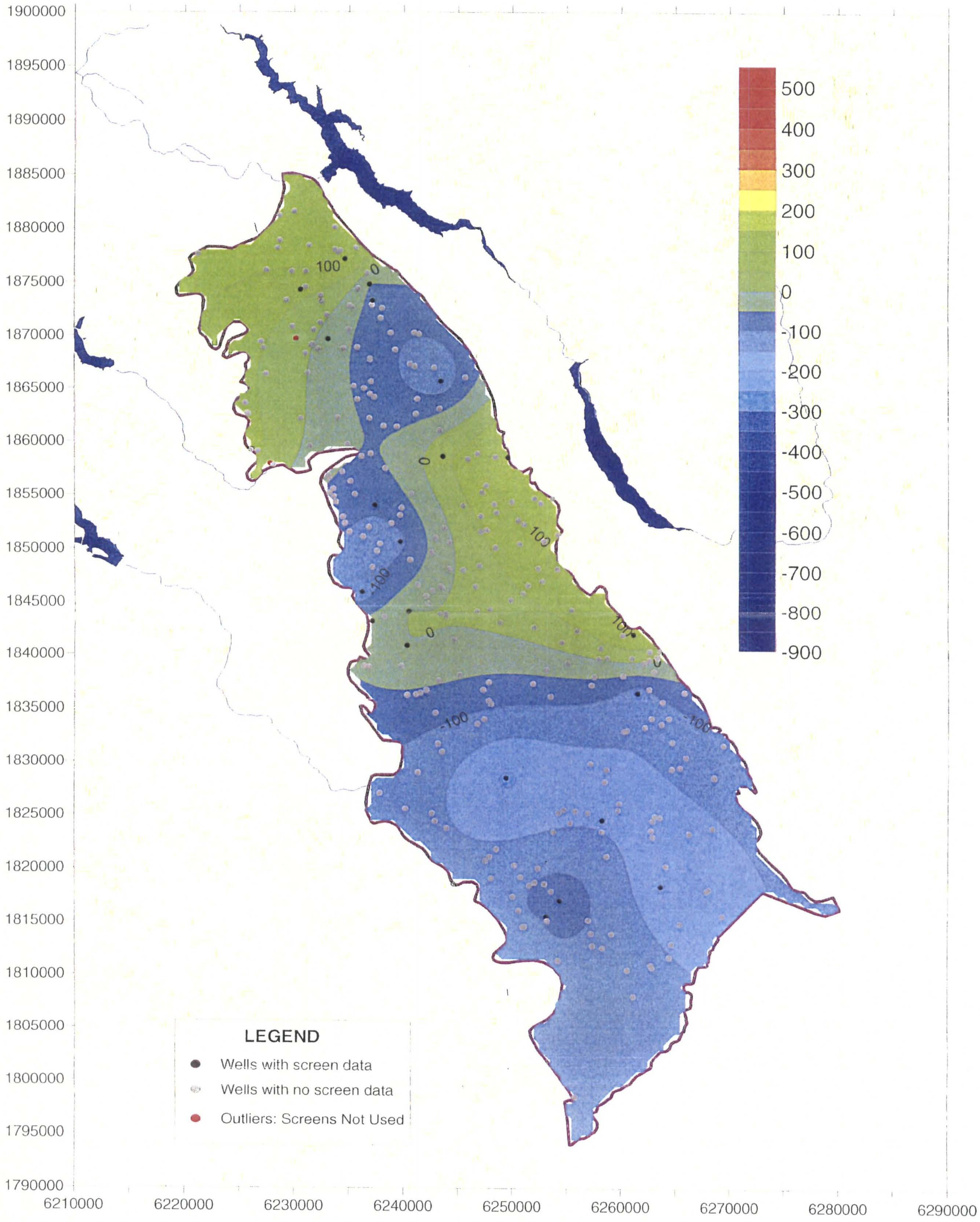


FIGURE A-4
AG WELLS WITH AND WITHOUT SCREEN DATA AFTER DATABASE UPDATE

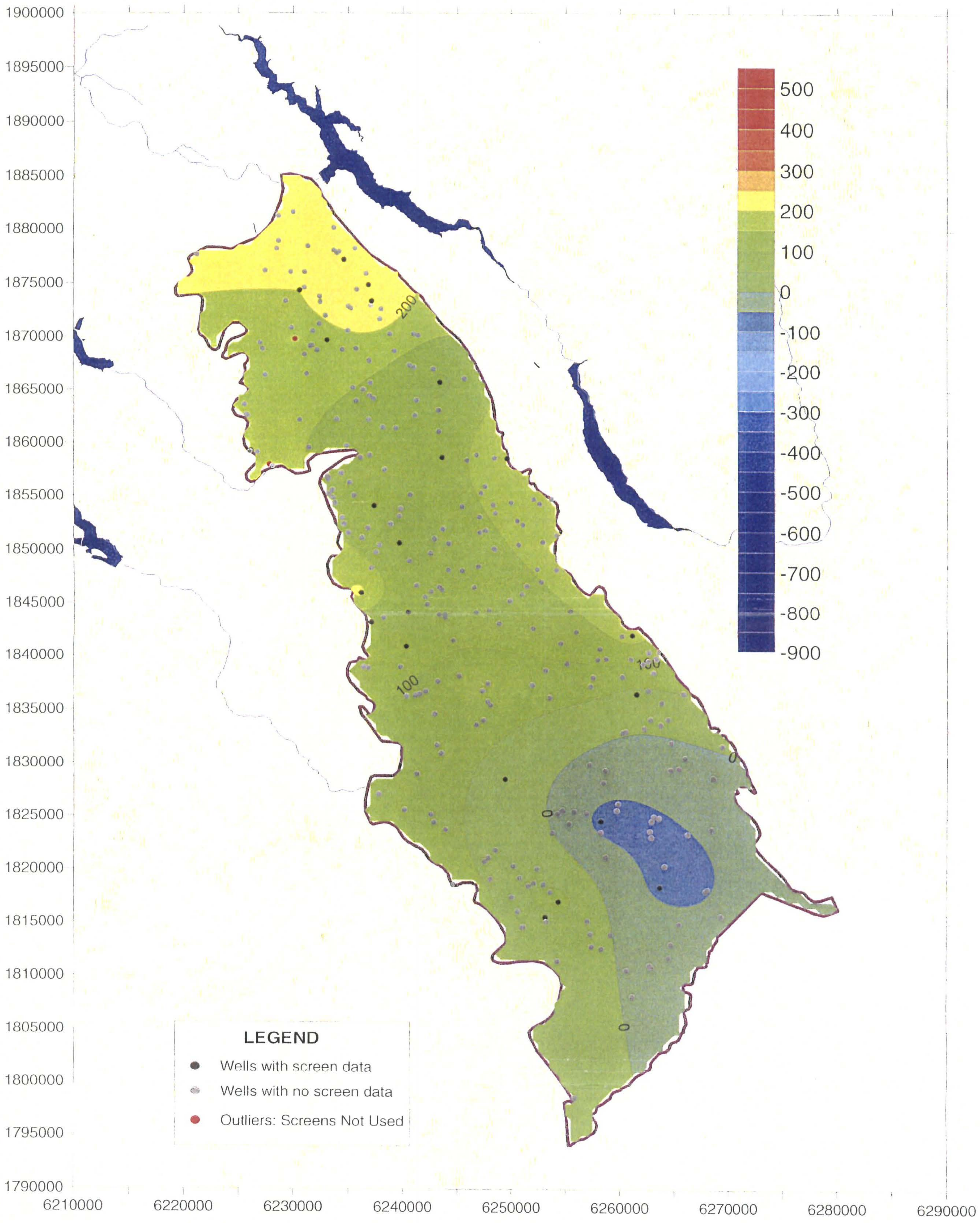
LLAGAS SUBBASIN GROUNDWATER MODEL
SANTA CLARA VALLEY WATER DISTRICT

Pumping_Screen_Analysis.xls -- C-AG (2) -- 04/15/2004

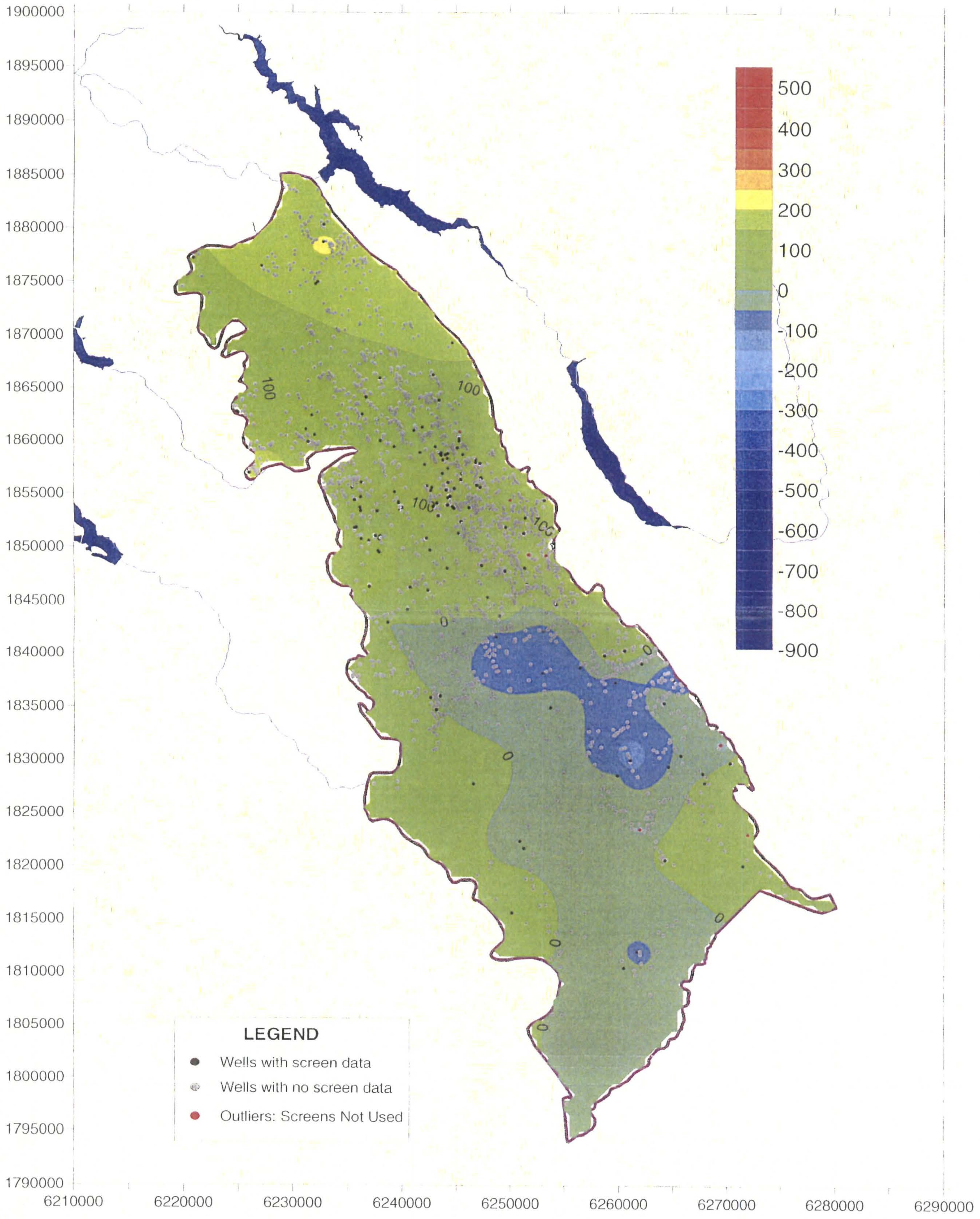
Elevation of Bottom of Screen (ft MSL)
NP Wells



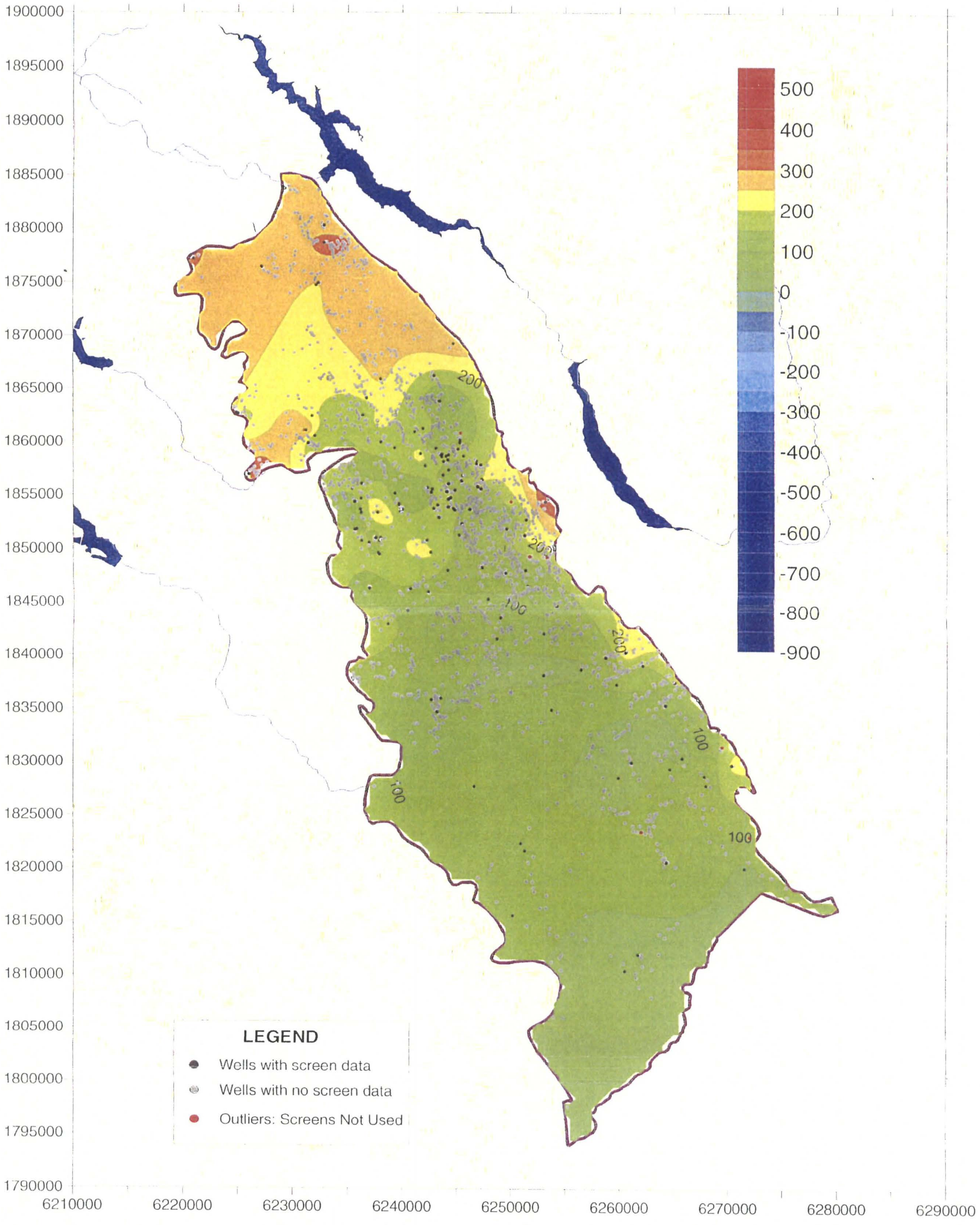
Elevation of Top of Screen (ft MSL)
NP Wells



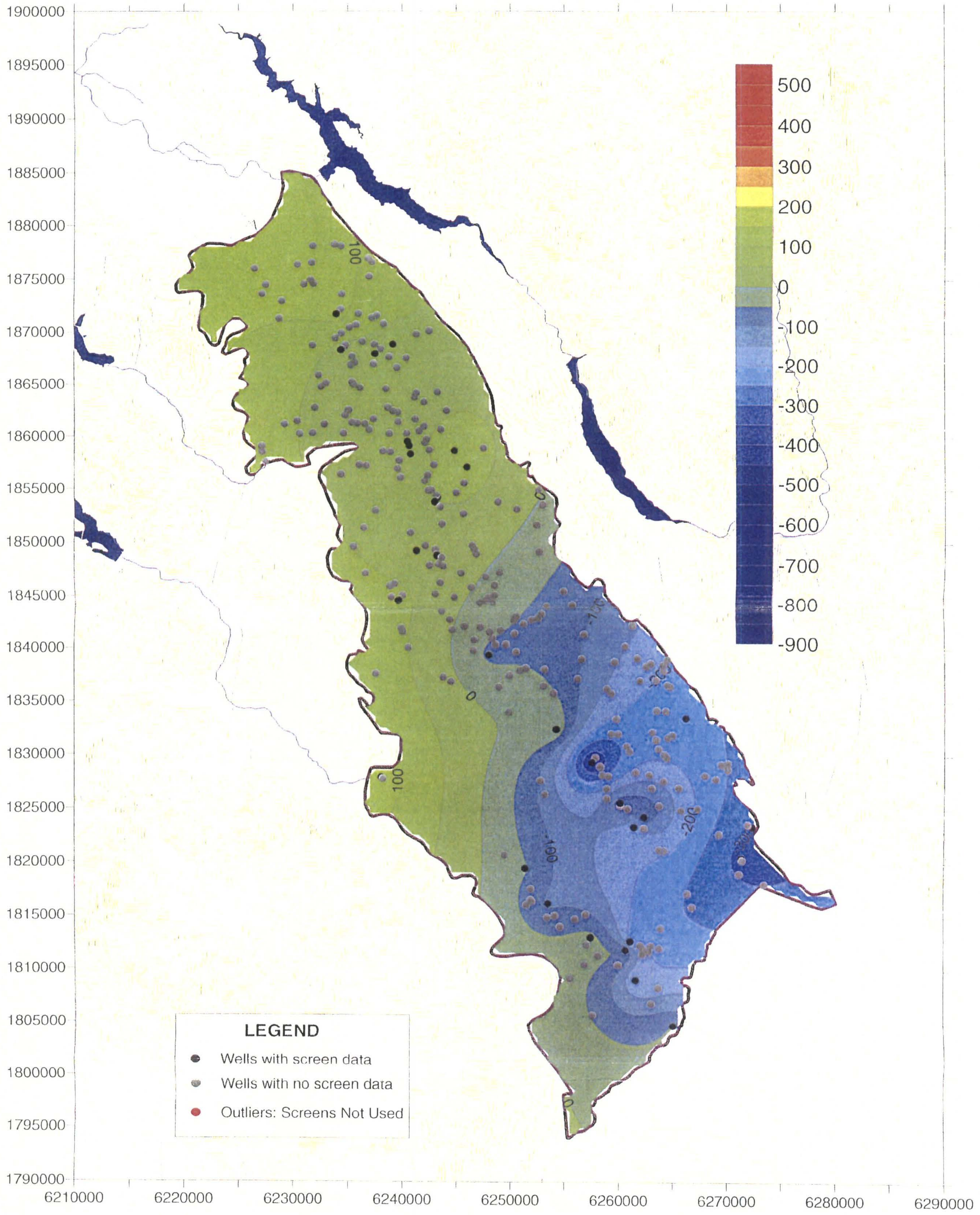
Elevation of Bottom of Screen (ft MSL)
DO Wells



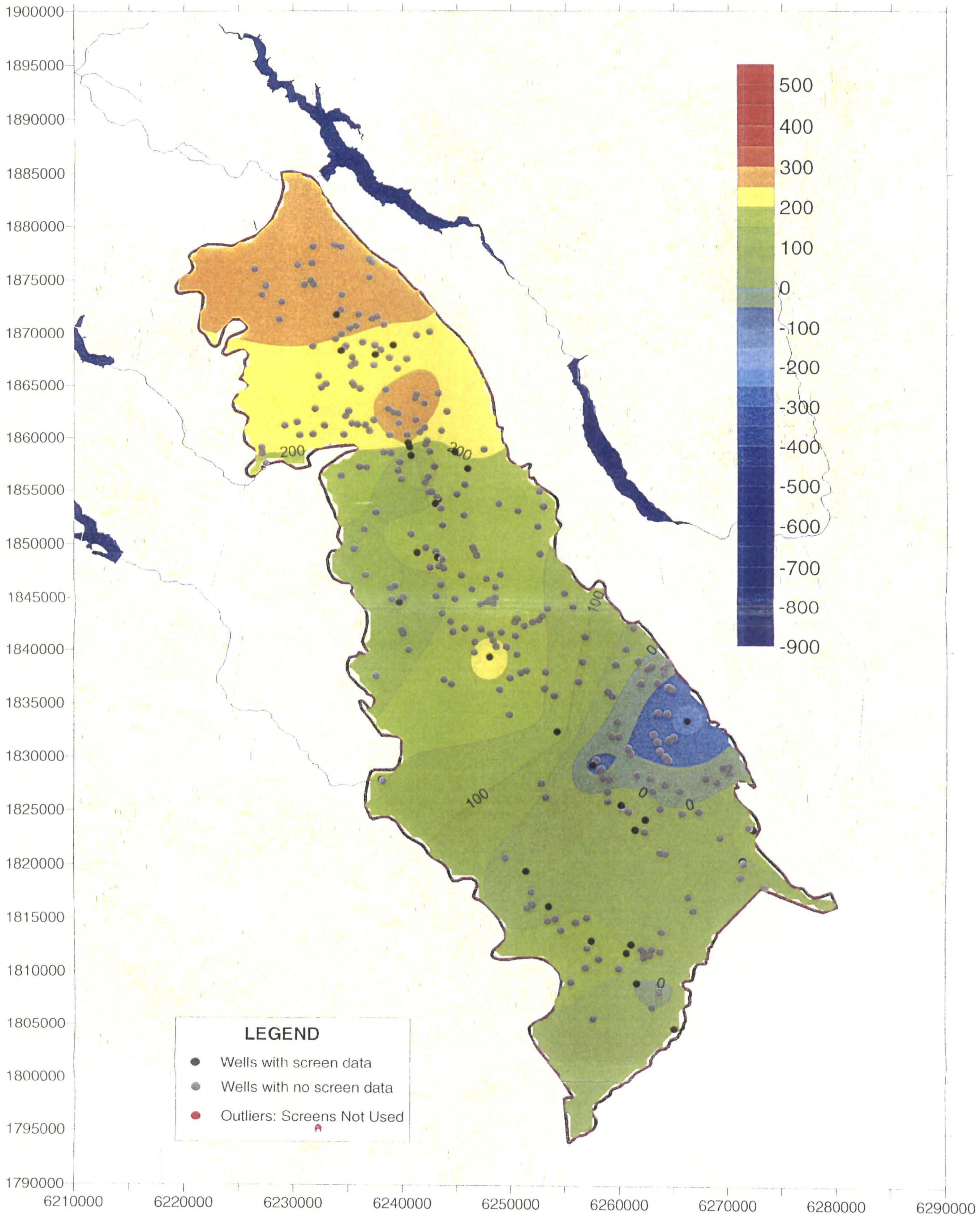
Elevation of Top of Screen (ft MSL)
DO Wells



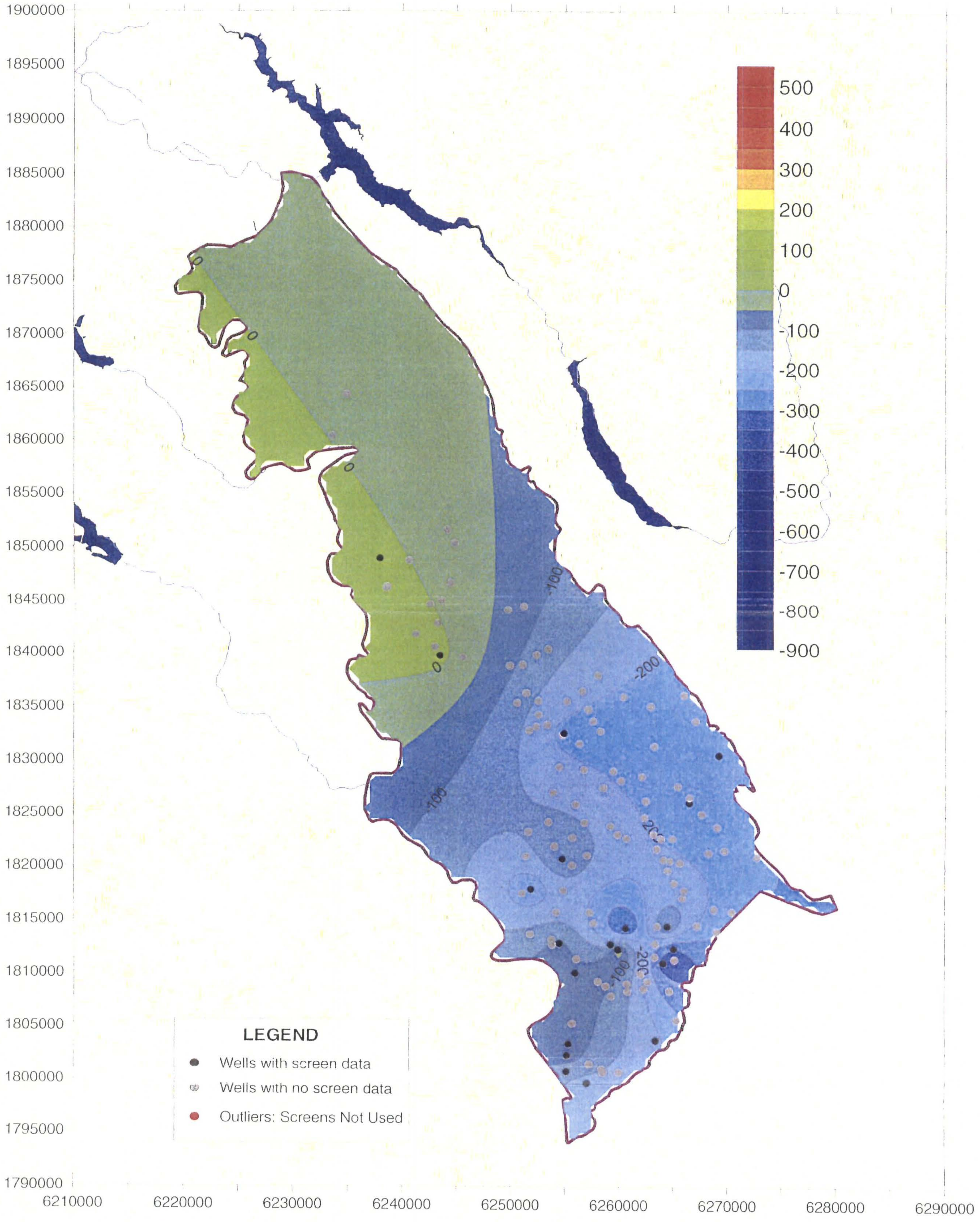
Elevation of Bottom of Screen (ft MSL)
AG Wells, Non-Zero Average < 50 AF/yr



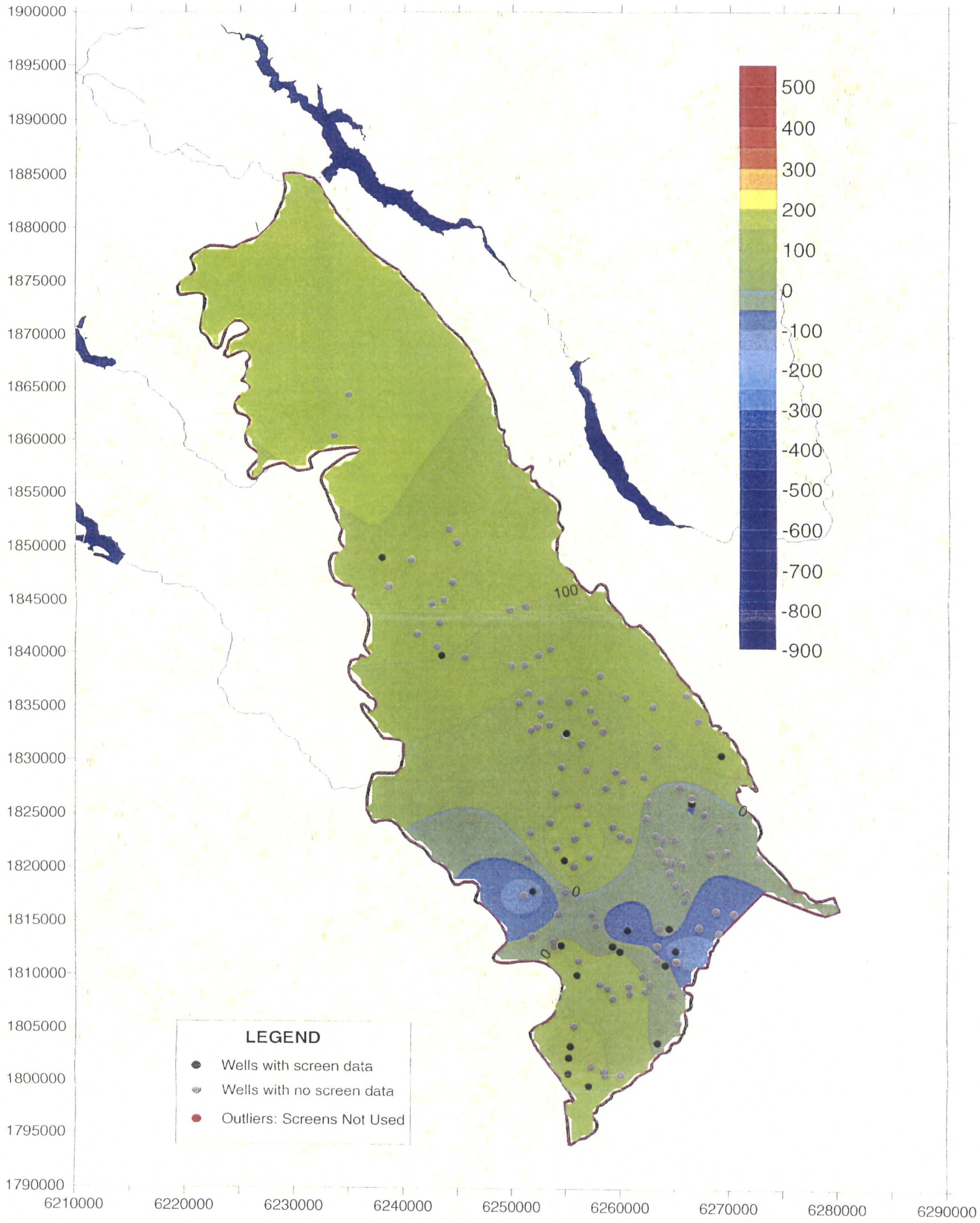
Elevation of Top of Screen (ft MSL)
AG Wells, Non-Zero Average < 50 AF/yr



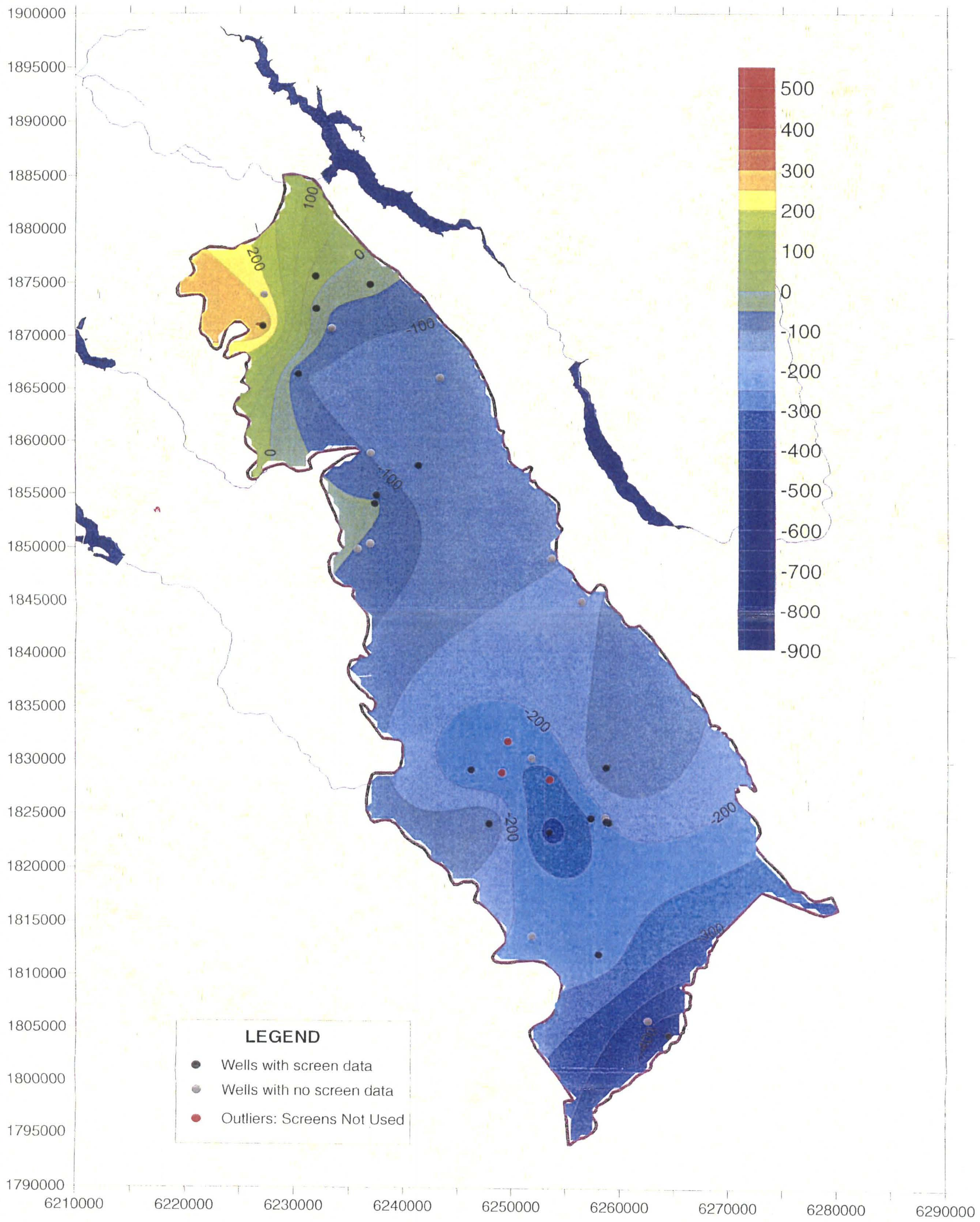
Elevation of Bottom of Screen (ft MSL)
AG Wells, Non-Zero Average > 50 AF/yr



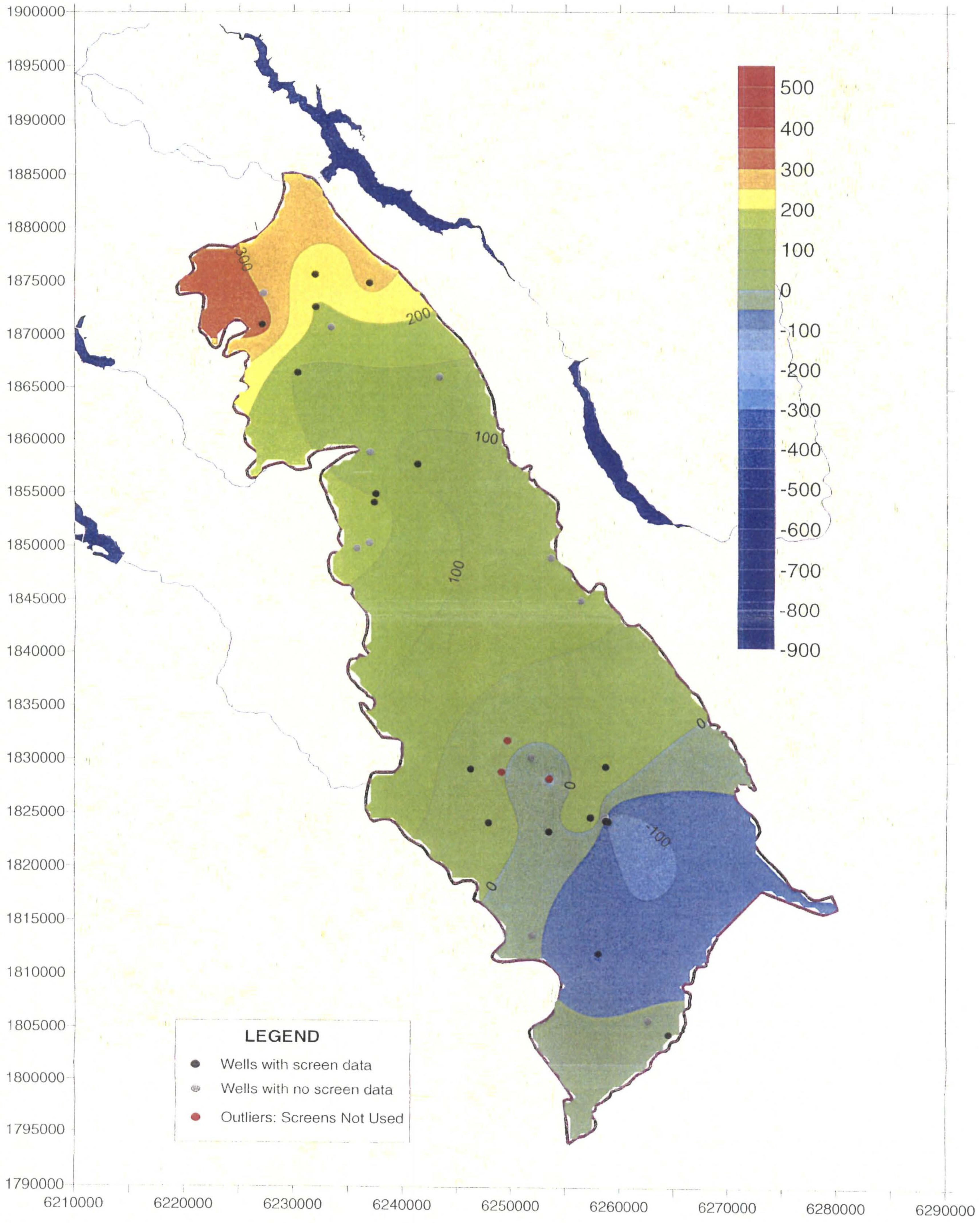
Elevation of Top of Screen (ft MSL)
AG Wells, Non-Zero Average > 50 AF/yr



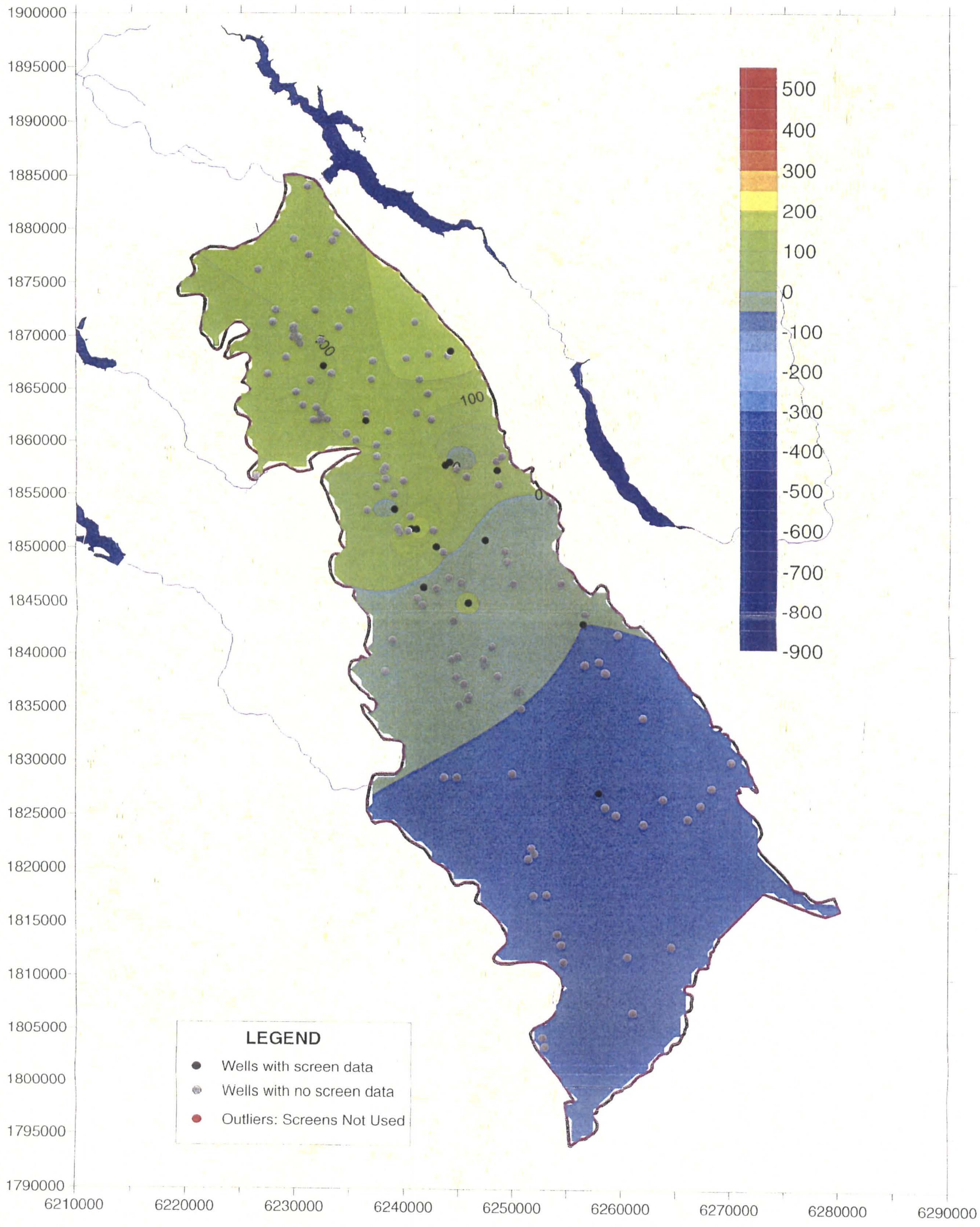
Elevation of Bottom of Screen (ft MSL)
MU Wells, Non-Zero Average > 50 AF/yr



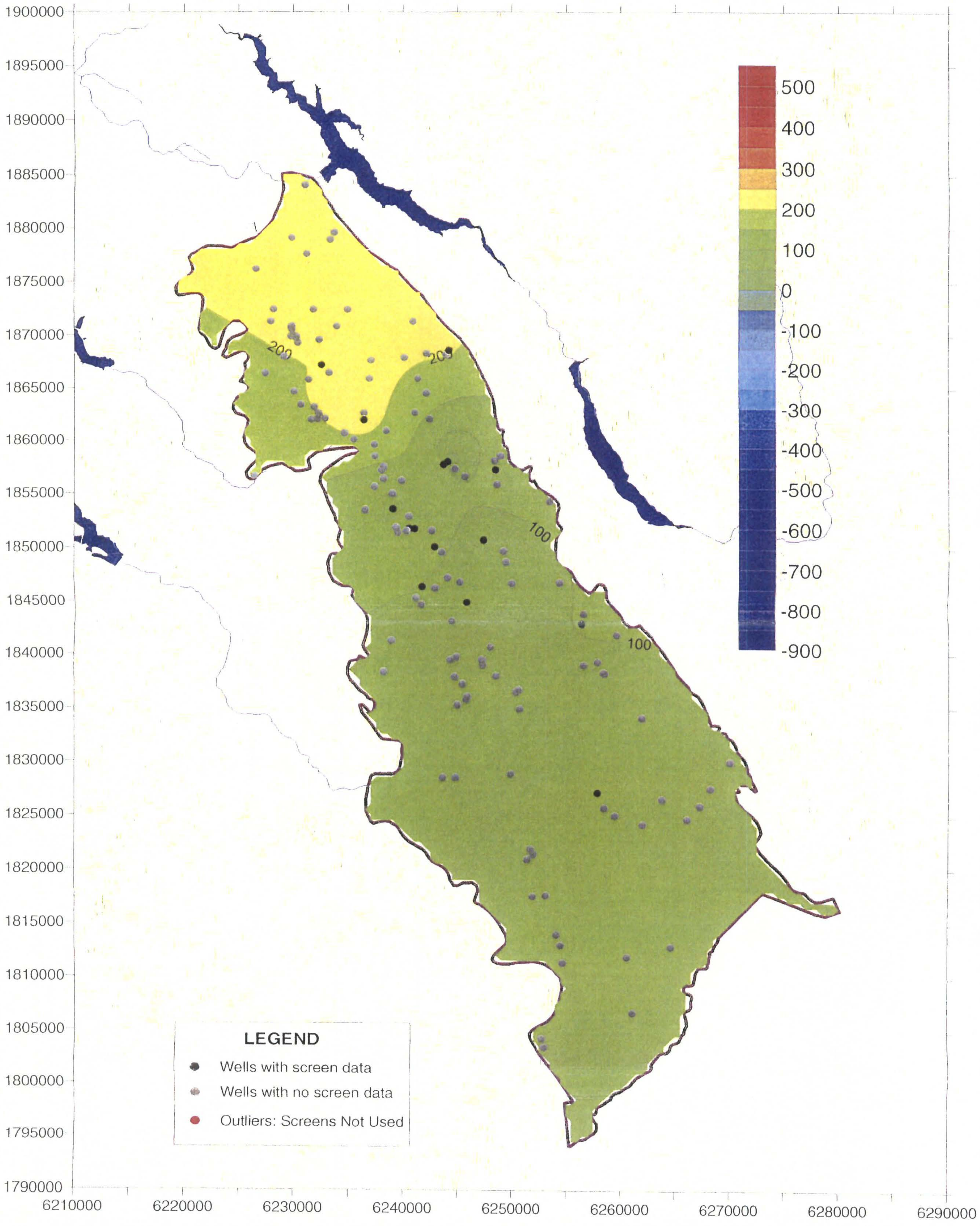
Elevation of Top of Screen (ft MSL)
MU Wells, Non-Zero Average > 50 AF/yr



Elevation of Bottom of Screen (ft MSL)
MU Wells, Non-Zero Average < 50 AF/yr



Elevation of Top of Screen (ft MSL)
MU Wells, Non-Zero Average < 50 AF/yr



APPENDIX B

Appendix B
Summary of Files Used for Modeling

APPENDIX B

B.1 Llagas Model Pre-Processing

This document summarizes pre-processors that were developed and used in support of the Llagas Basin groundwater model. The pre-processors were designed to manipulate and transfer data into a format suitable for input to Groundwater Vistas, the interface used to support modeling. Pre-processors were developed for two MODFLOW packages, the recharge and well packages. The recharge package is used to simulate deep percolation of precipitation and applied irrigation water. In addition to simulating groundwater pumping from wells, the well package is used to simulate subsurface inflow from uplands, stream seepage (small streams not directly in the model), intentional recharge, and septic recharge. All processors are described below, and are grouped according to the physical process that is being simulated.

B.1.1 Recharge

The recharge package is used to simulate deep percolation of precipitation and applied irrigation water. Recharge is calculated based on a soil moisture model that calculates the recharge rate for each land use and time period. For a given cell and a given stress period, recharge is calculated as the average recharge rate of land use types within the cell, weighted by area (sum of the product of acreage and recharge rate for each land use type, divided by the total acreage of the cell). To create recharge files, it is necessary to 1) calculate land use acreage for each cell at each stress period, 2) calculate recharge rates for each land use type and stress period, 3) calculate a single recharge rate for each cell and stress period based on land use, and 4) convert the data into a format that can be imported into Groundwater Vistas. Each of these four processes is discussed below.

Land Use Acreage

Land use types were grouped into eight categories:

Group1	**Alfalfa, Pasture and Turf - I**
Group2	**Barren Lands - NI**
Group3	**Native Vegetation - NI**
Group4	**Truck Crops AND Field Crops - I**
Group5	**Urban**
Group6	**Water**
Group7	**Wine Grapes AND Deciduous AND Citrus and Subtropical - I**
UK	**Unknown**

GIS is used to convert 1990 and 1998 land use coverages to a database table containing acreage of each land use type for every cell. Land use acreage was linearly interpolated for all stress periods based on the two land use coverages. The resultant table is imported into the recharge database (*Llagas_Recharge.mdb*) as "tbl_LandUse_AllCells."

Recharge Rates by Land Use

Recharge rates are calculated based on a soil moisture model. The soil moisture model consists of a set of seven Microsoft Excel files. Each Excel file is tagged with a letter at the beginning of the file name, going from A to G. Files build upon one another in alphabetic order (for example, G compiles information from D, E, and F), but are not linked. Results must be copied and pasted into the sequential files. Separate files are used to calculate recharge on irrigated lands (files A-*.xls through D-*.xls) and non-irrigated lands (native vegetation: *E-6-month-SCmodel-nativeveg.xls* and barren soils: *F-6-month-SCmodel-baresoil.xls*).

Recharge for irrigated lands is further subdivided and calculated as recharge from precipitation and recharge from applied irrigation. Recharge from precipitation is calculated in *C-6-month-SCmodel-irrigcrops.xls*. Recharge from applied irrigation is calculated on an annual basis in *B-SCModel-IrrigAg.xls*. File *D-IrrigAg-irrig.xls* sums up the recharge from precipitation and irrigation. File *D-IrrigAg-irrig.xls* also distributes the annual return flow of applied irrigation based on the distribution of evapotranspiration rates in *A-ETaw.xls*. ***NOTE: There may be an error in file D*. Tab "RF-irrig+precip on irrig" uses alfalfa rates from November rather than the average of Apr-Sep as it should.***

Results from files D-*.xls through F-*.xls (recharge for irrigated land, native vegetation, and barren soils) are compiled in *G-semester-DeepPerc.xls*.

Recharge rates from *G-semester-DeepPerc.xls* are pasted into tab "Calculated_RCH_Rates" in *WaterBudget_Controls.xls*. Calculated recharge rates are adjusted to account for the differences between acreage from the land use maps and actual irrigated acreage (data from Santa Clara Valley Water District). The tab "Recharge_dbImport" in *WaterBudget_Controls.xls* contains adjusted recharge rates in the correct units to be imported into the recharge database (*Llagas_Recharge.mdb*). It is imported into table "lut_RechargeRates."

Recharge Rates at Model Cells

Calculation of recharge at each cell and each stress period is performed using a Microsoft Access query in the recharge database (*Llagas_Recharge.mdb*). The query is titled "qry_MakeTable_Recharge_By_Semester." It calculates the average recharge rate of land use types within each cell, weighted by area (sum of the product of acreage and recharge rate for each land use type, divided by the total acreage of the cell). The table "tbl_Recharge_All_Semesters" is then exported as a *.csv file. Upon export, it is necessary to remove the default text qualifier quotes in the RCH field.

Conversion and Import to Groundwater Vistas

A Microsoft Excel macro is used to convert the *.csv file of recharge at every model cell and time period into a format that can be imported into Groundwater Vistas. The macro, along with instructions for conversion and importing, is found in *RCH_db2Vistas.xls*.

B.1.2 Wells

The MODFLOW well package is used to simulate several water budget components in addition to groundwater pumping. Other processes include subsurface inflow from uplands, stream seepage (small streams not directly in the model), intentional recharge, and septic recharge, and are all simulated as injection wells. A series of processors is used to convert "well" pumping and injection rates into a single file to import into Groundwater Vistas. The single import file is generated using a macro in the Excel file *Llagas VM-GWV Generator.xls*. *Llagas VM-GWV Generator.xls* contains data pasted from two other files that calculate pumping and injection rates. The files used for calculation are discussed below, followed by a description of the generator file itself.

B.1.2.1 Groundwater Pumping

Groundwater pumping data in units of acre-feet per semester are pasted into an Excel file. This file converts database pumping rates (AF) to MODFLOW units (ft^3/day). A link exists between the pumping generator file and the pumping rates in *Llagas_Generator_Prep_File.xls*. Well perforations must be manually pasted into the "WEL Perfs" tab of *Llagas VM-GWV Generator.xls*. Perforations must have the same names and be in the same sequential order as the "WEL" tab, as discussed in the Well Generator File section below.

B.1.2.2 Other Water Budget Components

The spreadsheet *WaterBudget_Controls.xls* is used to calculate the following water budget components: 1) subsurface inflow from uplands, 2) stream seepage (small streams not directly in model), 3) intentional recharge, and 4) septic recharge. As with *Llagas_Generator_Prep_File.xls*, the generator file links directly to the "Master" tab of *WaterBudget_Controls.xls* for all pumping rates. Well perforations must be manually updated in the well generator file if any changes are required. Each water budget component is described below.

Subsurface Inflow from Uplands

Subsurface inflow from uplands is calculated using Darcy's law, with input in the "Knobs" tab of *WaterBudget_Controls.xls*. Subsurface inflow is divided into eight drainages, A thru G. Wells are named A01, A02, etc. Screens are calculated based on the top and bottom of the model at its edges (5 feet below surface to 5 feet above bottom).

Stream Seepage (small streams not directly in model)

The percent of surface inflow from the eight adjacent drainages that infiltrates is specified in the "Knobs" tab of *WaterBudget_Controls.xls*. For each drainage, stream seepage is simulated using wells named StreamA01, StreamA02, etc. "Screens" of the wells are all set at 5-145 foot depths (layer 1 only).

Intentional Recharge

Known intentional recharge rates are pasted into tab "WY WB Worksheet." The values are linked to wells named after the recharge pond or creek (Church01, Church02, etc.). "Screens" of the wells are all set at 5-145 foot depths (layer 1 only).

Septic Recharge

For every domestic well outside of city limits (tab "DOPumpage_OutofCityLimits"), a well is used to simulate recharge from septic tanks. Recharge is calculated based on a percentage of pumping, specified in the tab "Knobs." Wells are named "Sep_StateWell#". "Screens" of the wells are all set at 5-145 foot depths (layer 1 only).

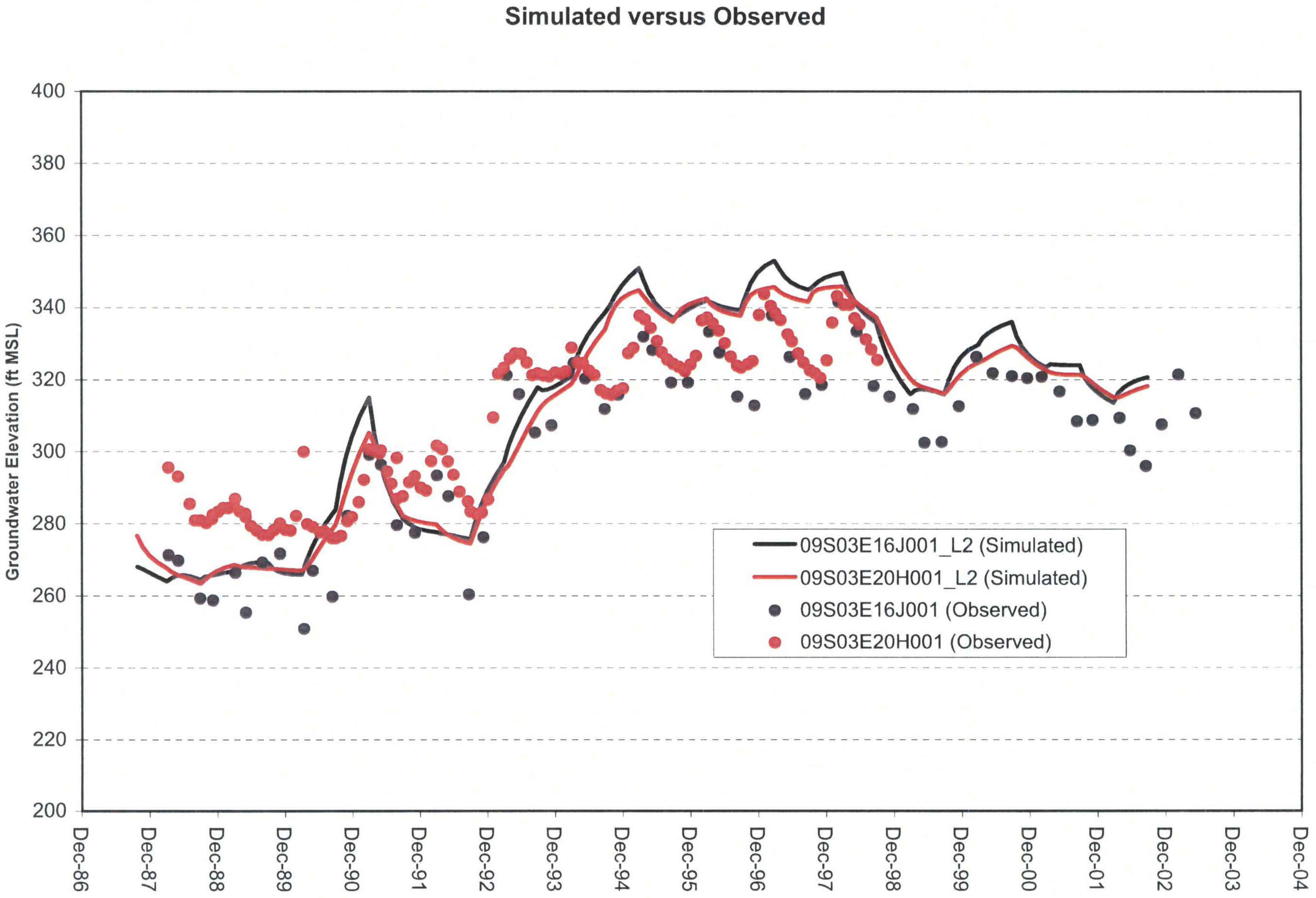
B.1.2.3 Well Generator File

All well data are converted to a format suitable for import to Vistas using *Llagas VM-GWV Generator.xls*. The "generator" has one tab for pumping rates ("WEL") and one tab for well perforations ("WEL Perfs"). All pumping rates ("WEL" tab) are pasted in manually from files *Llagas_Generator_Prep_File.xls* and *WaterBudget_Controls.xls*, which are discussed in the preceding section. Well perforations are pasted into the "WEL Perfs" tab of the generator. Wells must be in the same order in the pumping and perforations tabs. If new wells are added, they must be added using the "insert" command. New wells cannot be pasted at the bottom of the list, as there is a "tag" on the last line that the macro uses. Wells pasted at the end will not be "seen" by the macro.

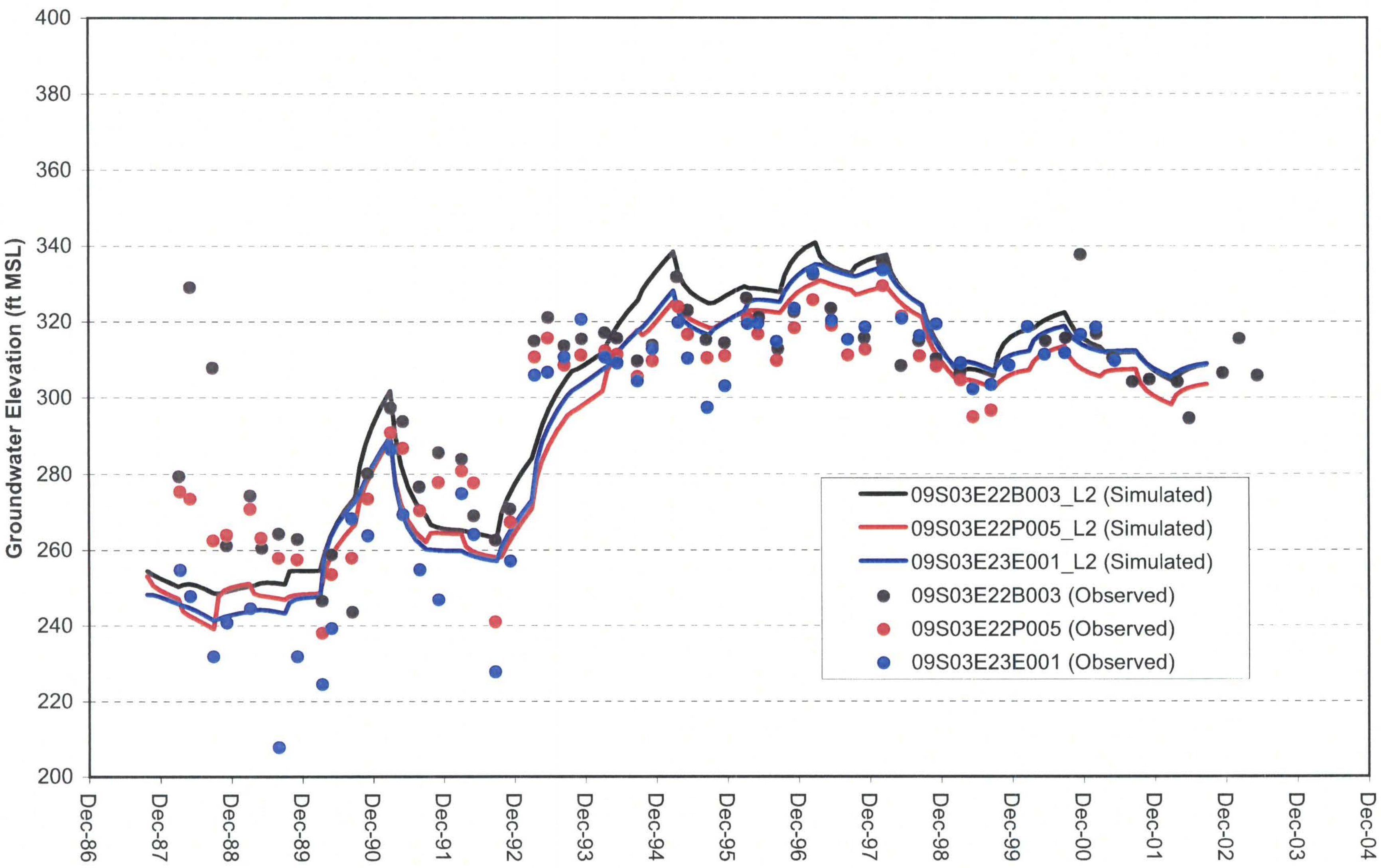
The macro to create the pumping file is located in the "Options" tab. A path and file name is entered and the macro is run using the "Create Files" button. Wells are imported into Vistas using the command Add | Import | Well, and browsing to the new file created by the generator.

APPENDIX C

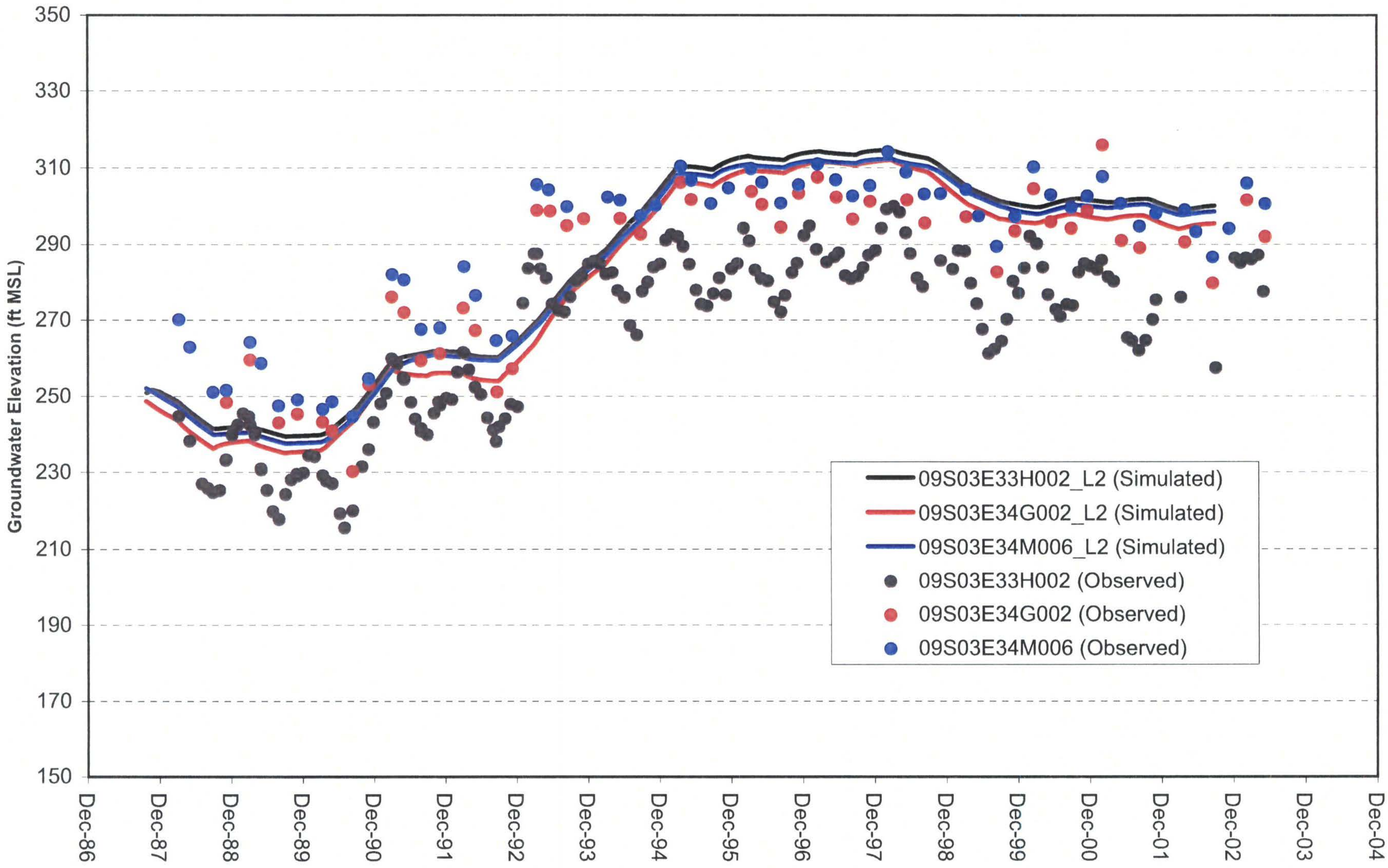
Appendix C
Calibration Hydrographs


Simulated versus Observed
Groundwater Elevation (ft MSL)
400
380
360
340
320
300
280
260
240
220
200
Dec-86
Dec-87
Dec-88
Dec-89
Dec-90
Dec-91
Dec-92
Dec-93
Dec-94
Dec-95
Dec-96
Dec-97
Dec-98
Dec-99
Dec-00
Dec-01
Dec-02
Dec-03
Dec-04
09S03E16J001_L2 (Simulated)
09S03E20H001_L2 (Simulated)
09S03E16J001 (Observed)
09S03E20H001 (Observed)

Simulated versus Observed

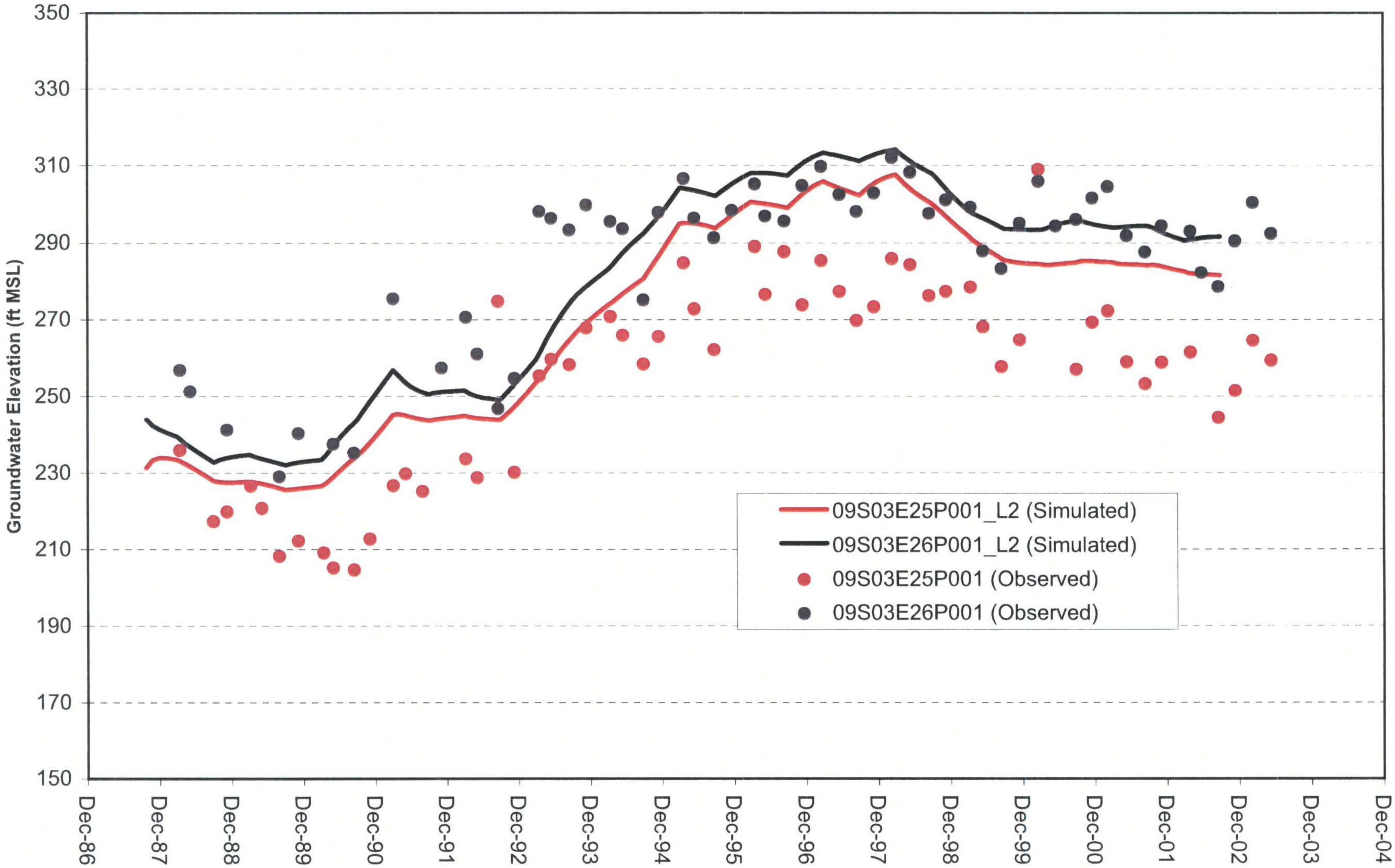


Simulated versus Observed



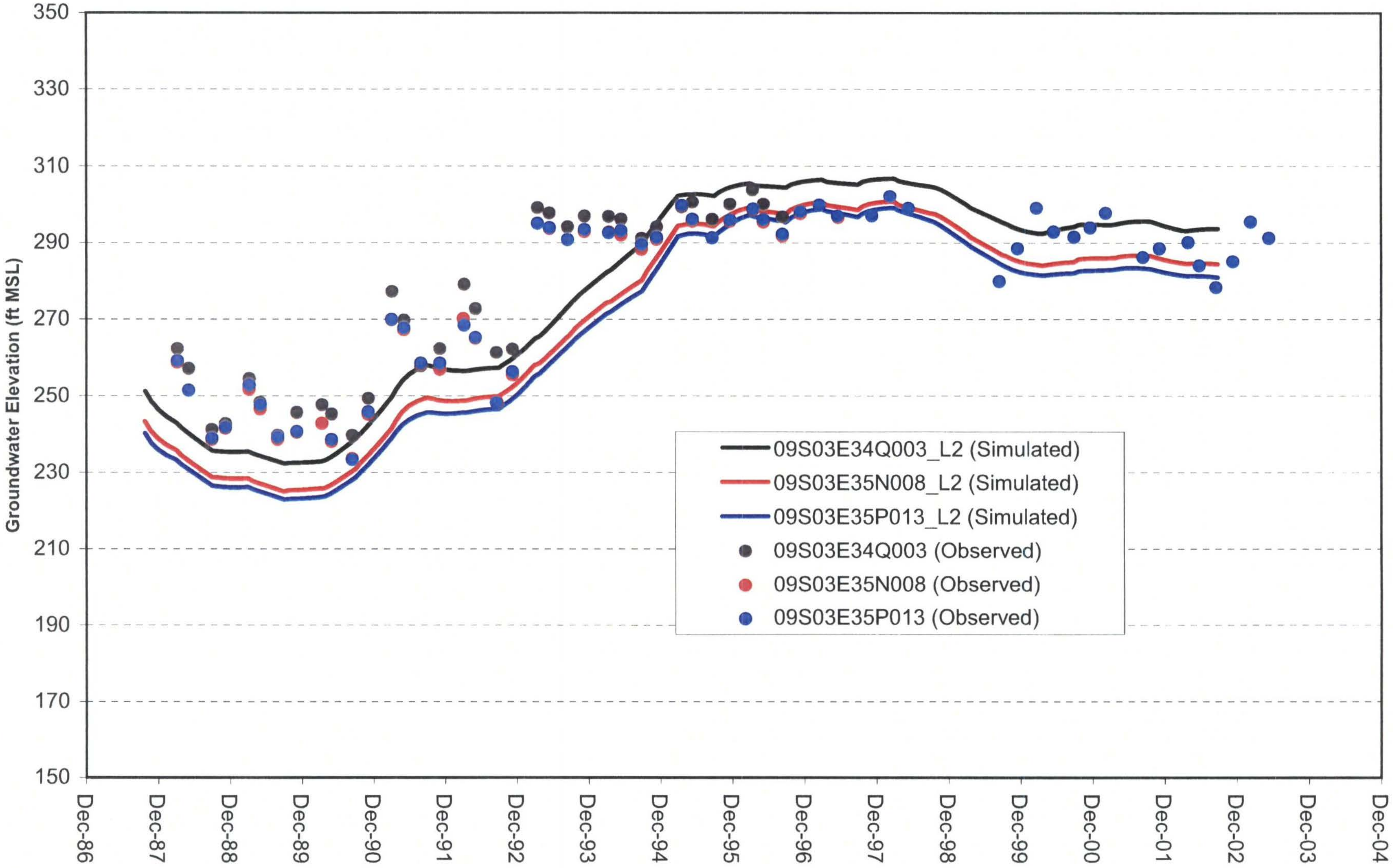
R133 Results.xls

Simulated versus Observed

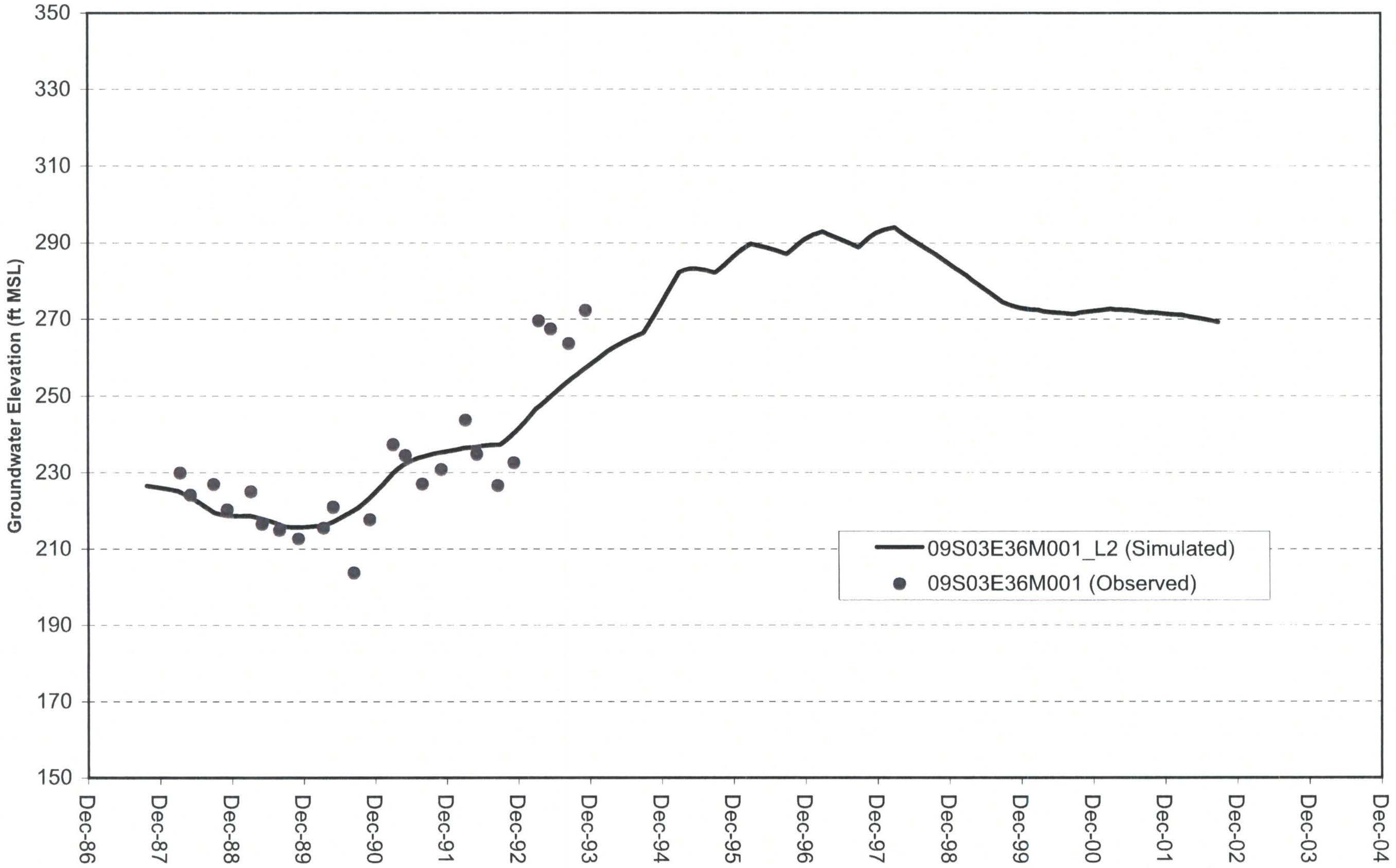


R133 Results.xls

Simulated versus Observed

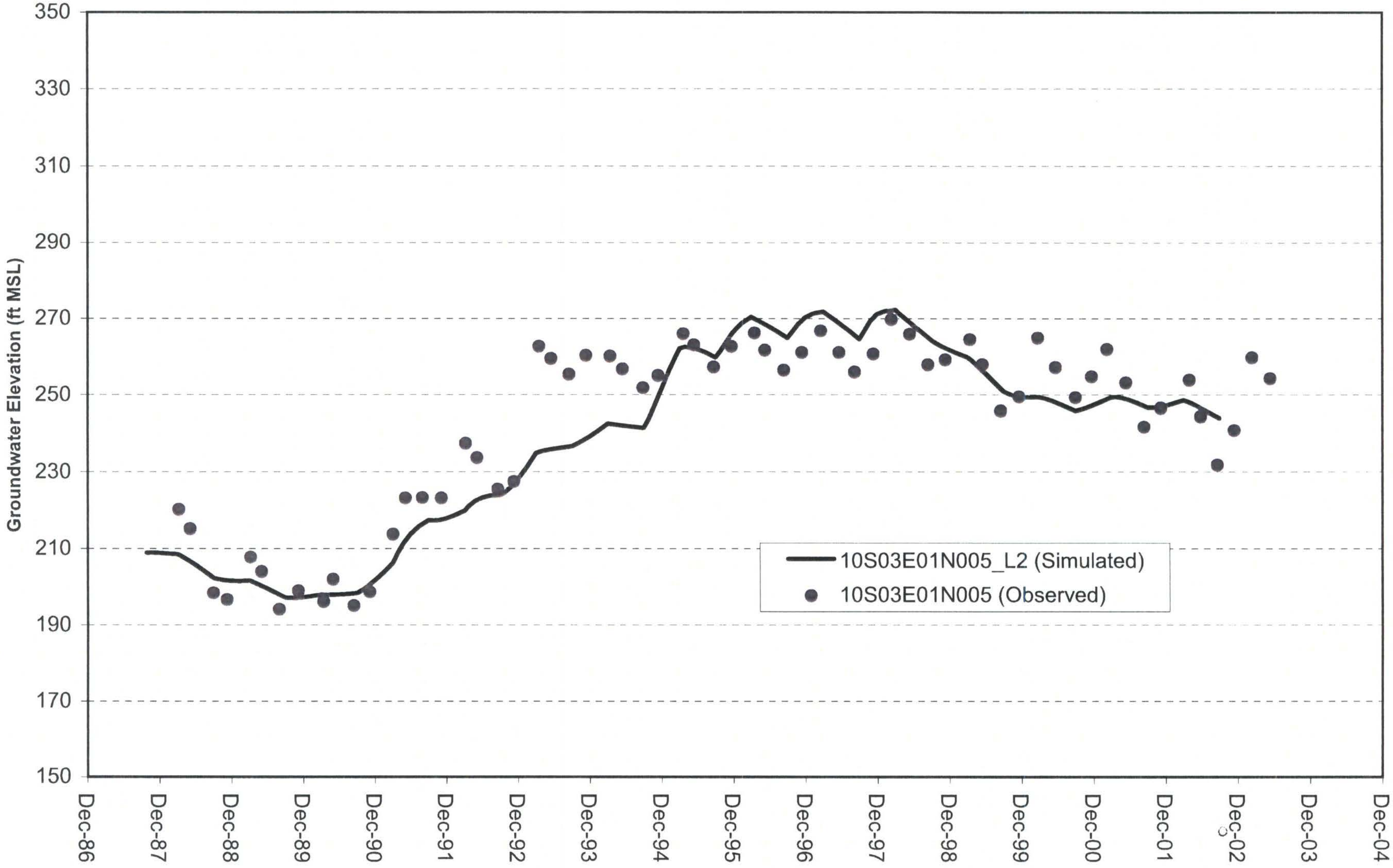


Simulated versus Observed

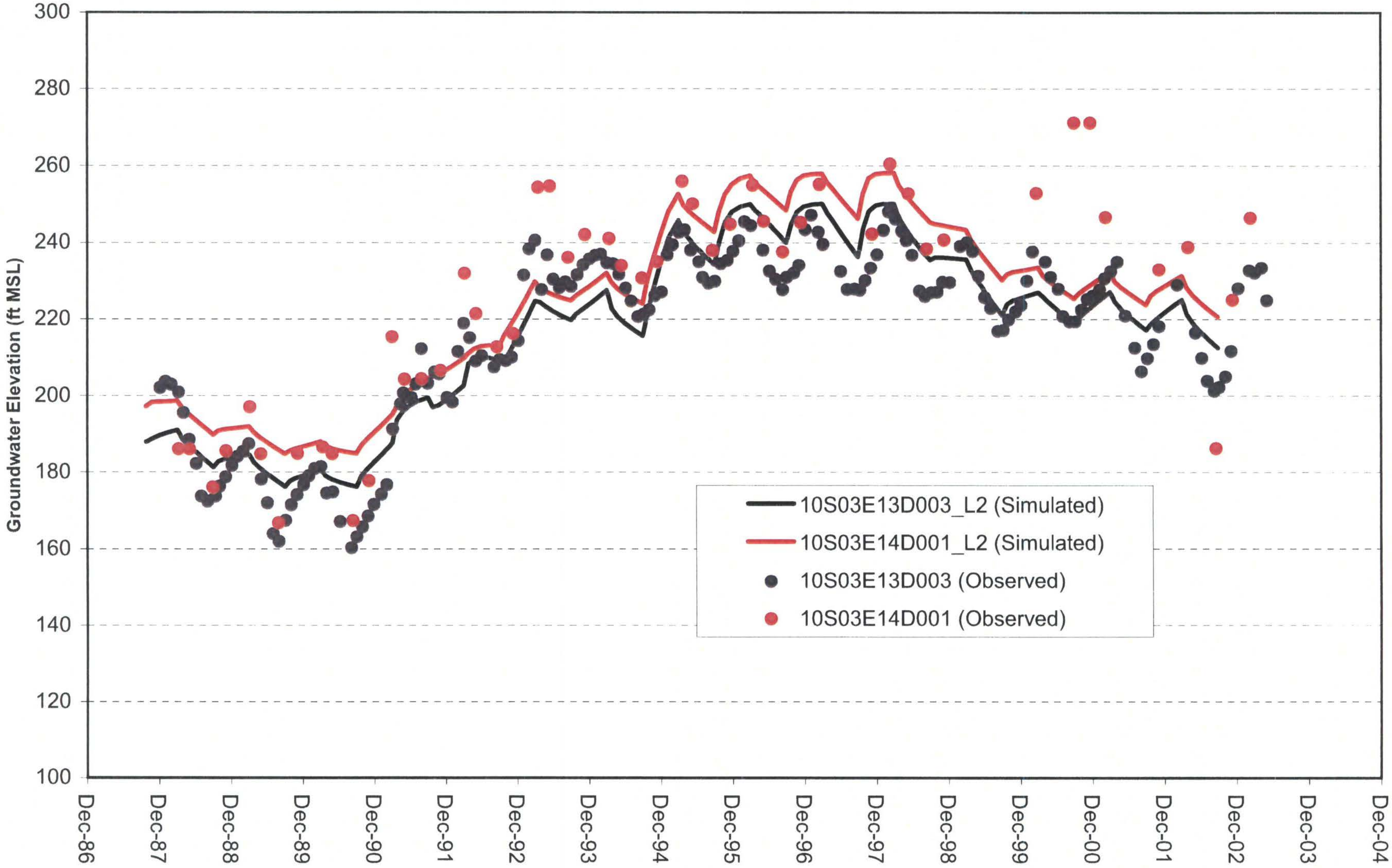


R133 Results.xls

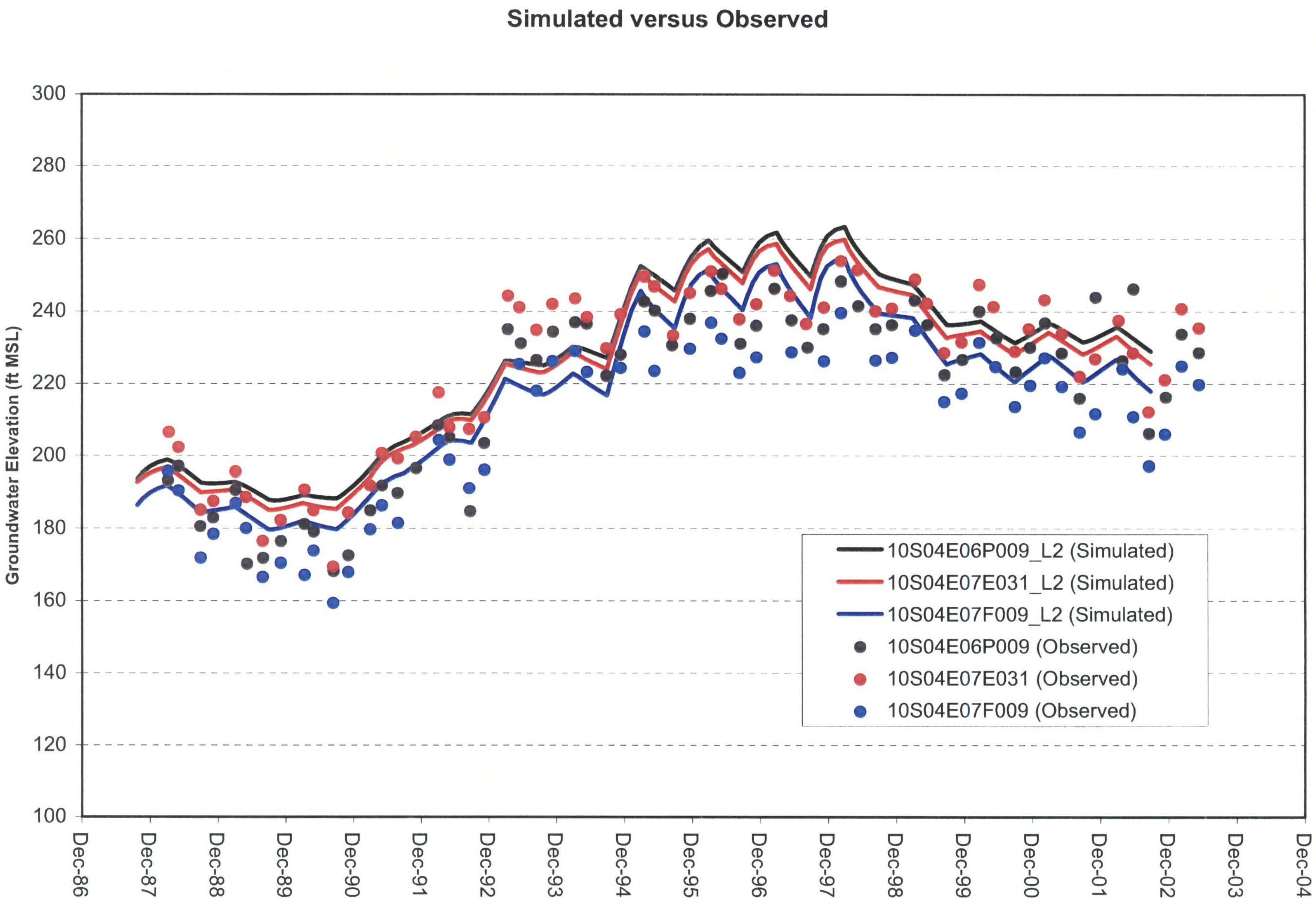
Simulated versus Observed



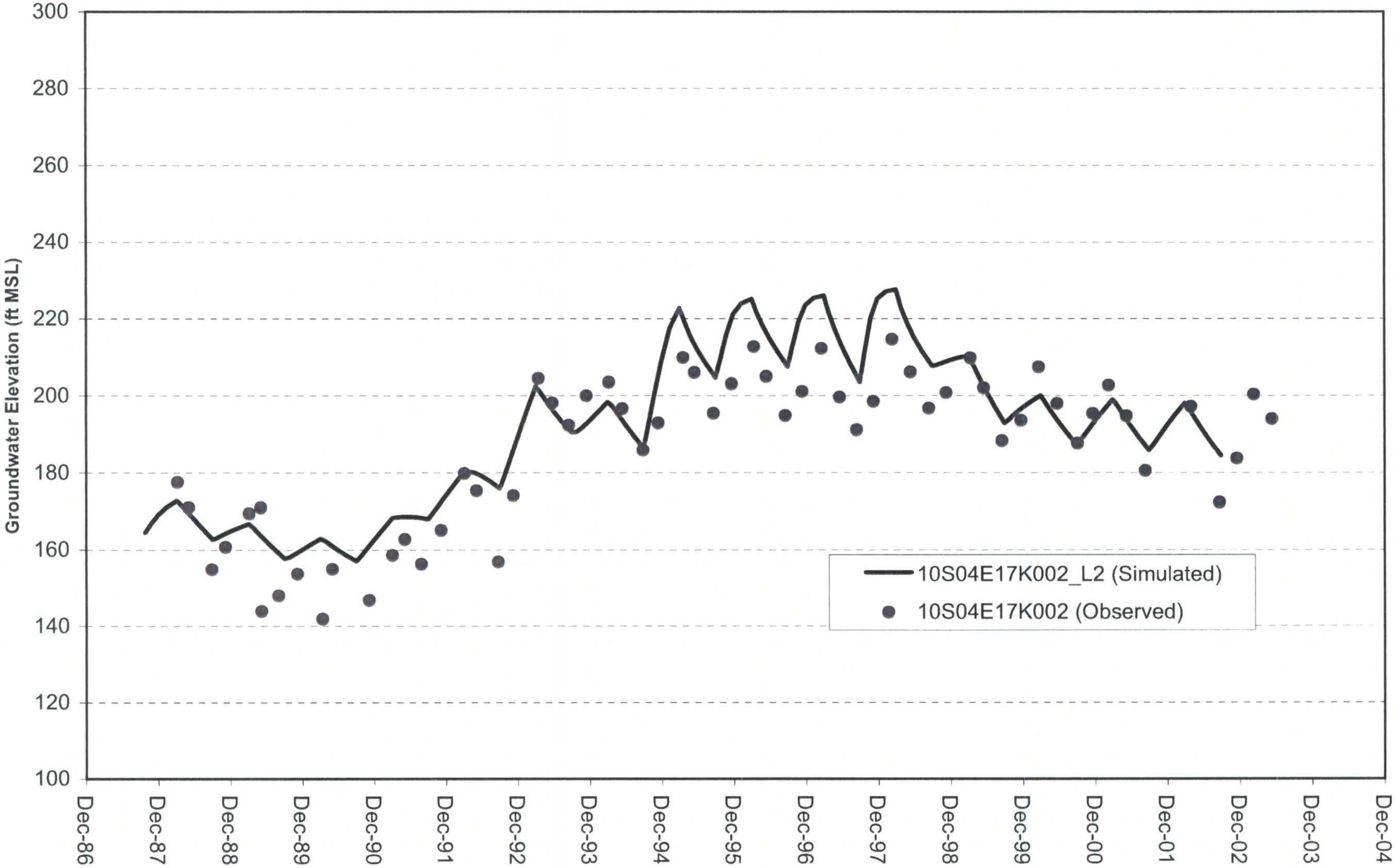
Simulated versus Observed



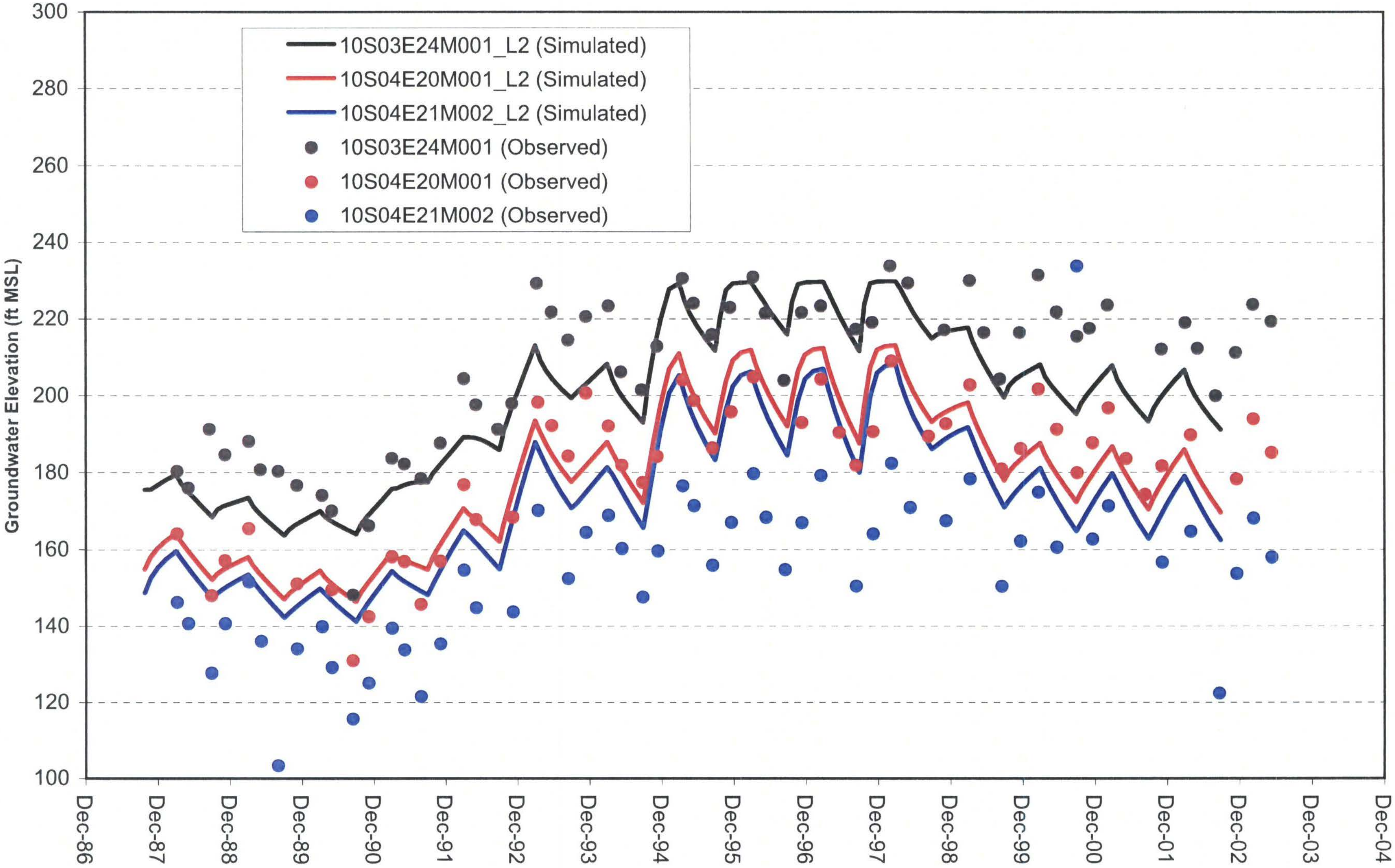
R133 Results.xls


Simulated versus Observed
Groundwater Elevation (ft MSL)
300
280
260
240
220
200
180
160
140
120
100
Dec-86
Dec-87
Dec-88
Dec-89
Dec-90
Dec-91
Dec-92
Dec-93
Dec-94
Dec-95
Dec-96
Dec-97
Dec-98
Dec-99
Dec-00
Dec-01
Dec-02
Dec-03
Dec-04
10S04E06P009_L2 (Simulated)
10S04E07E031_L2 (Simulated)
10S04E07F009_L2 (Simulated)
10S04E06P009 (Observed)
10S04E07E031 (Observed)
10S04E07F009 (Observed)

Simulated versus Observed

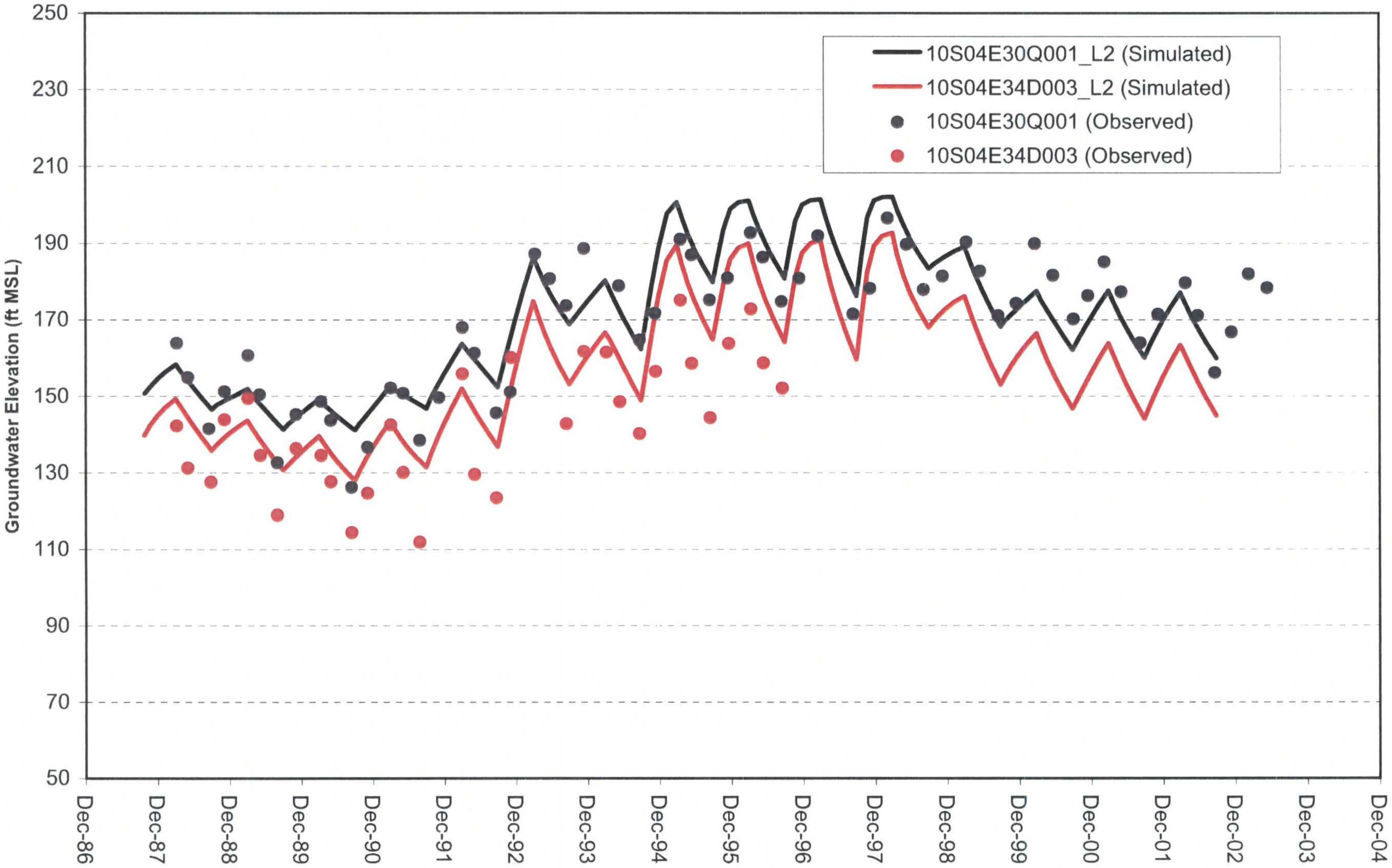


Simulated versus Observed

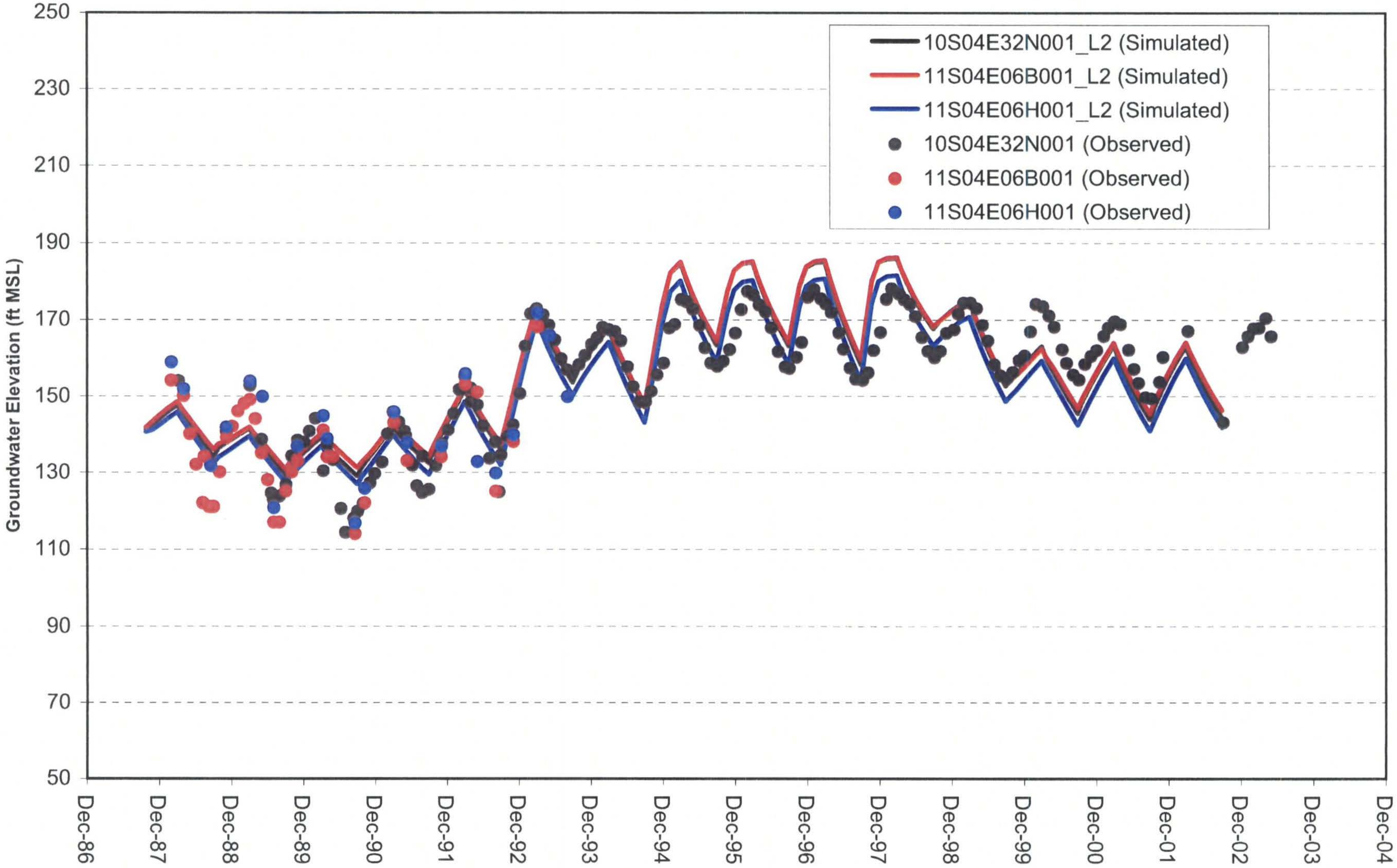


R133 Results.xls

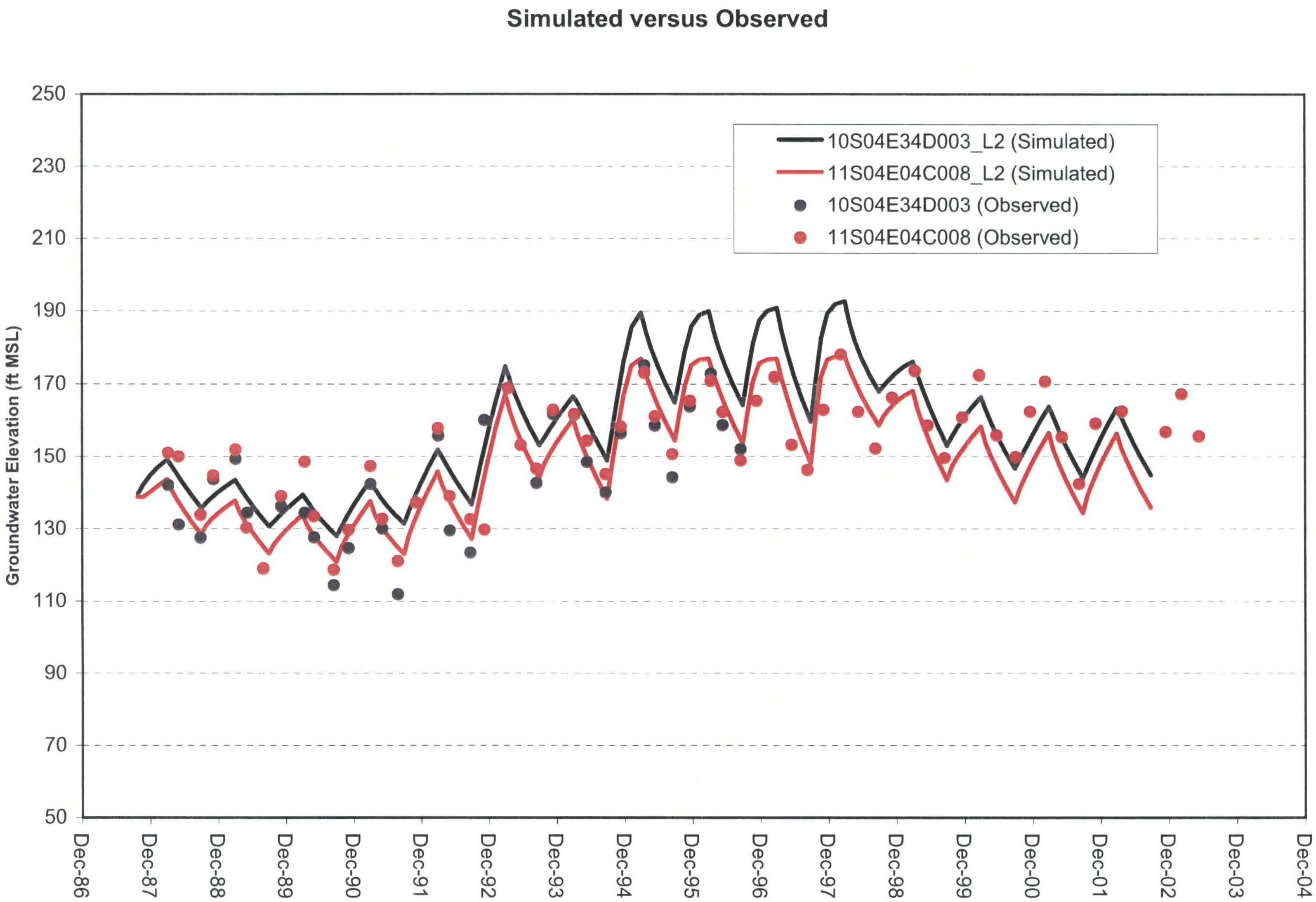
Simulated versus Observed



Simulated versus Observed

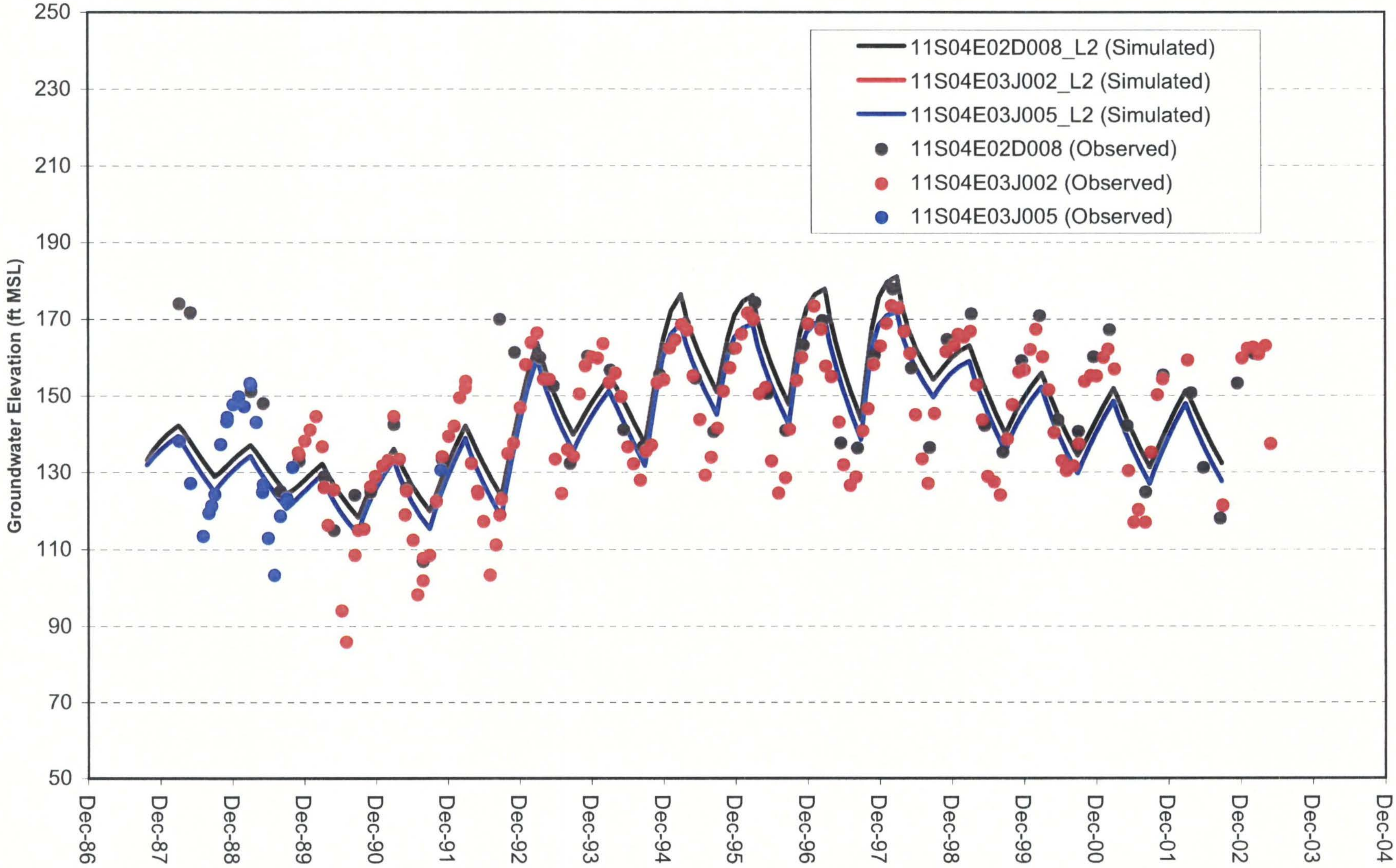


R133 Results.xls



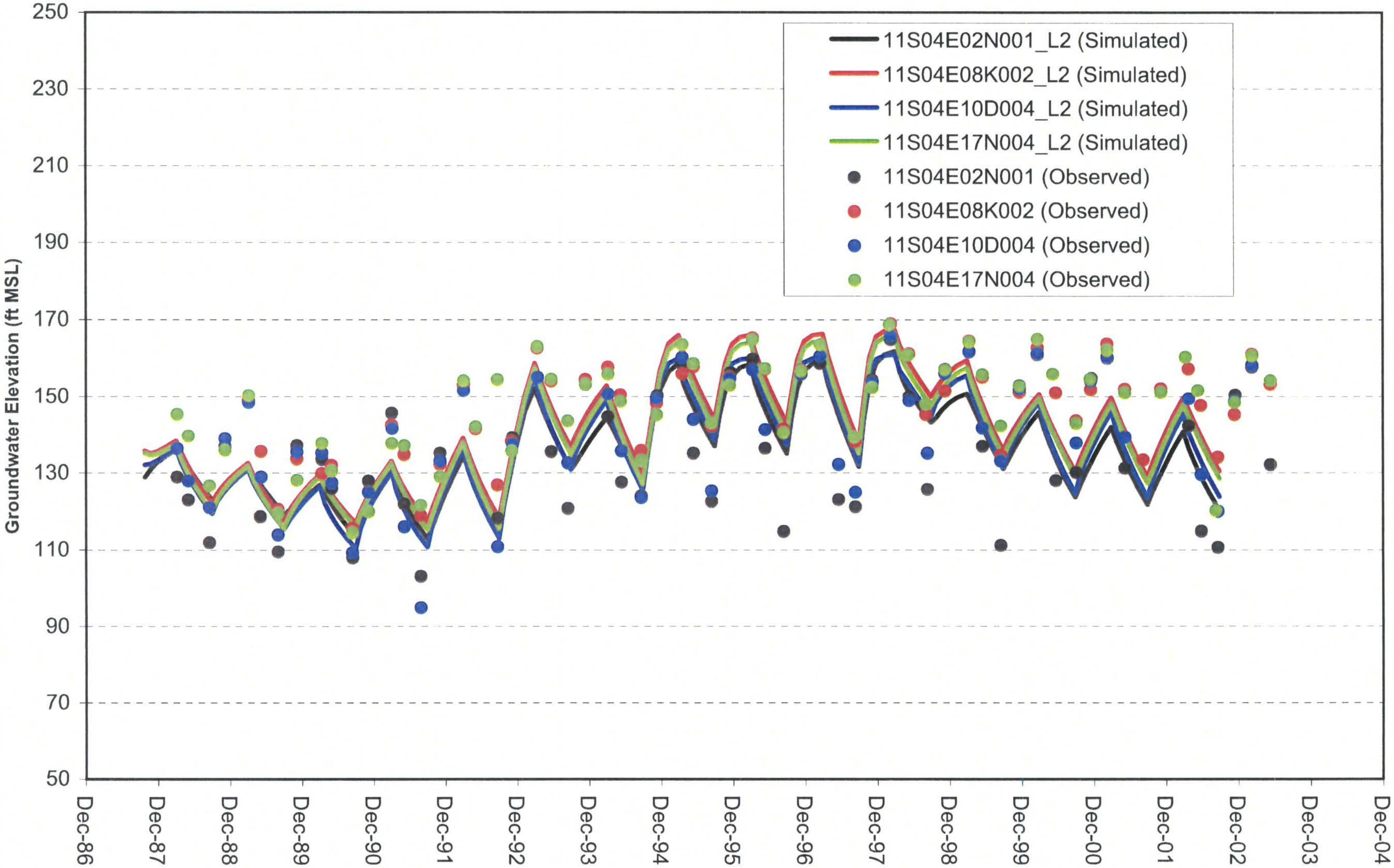
R133 Results.xls

Simulated versus Observed

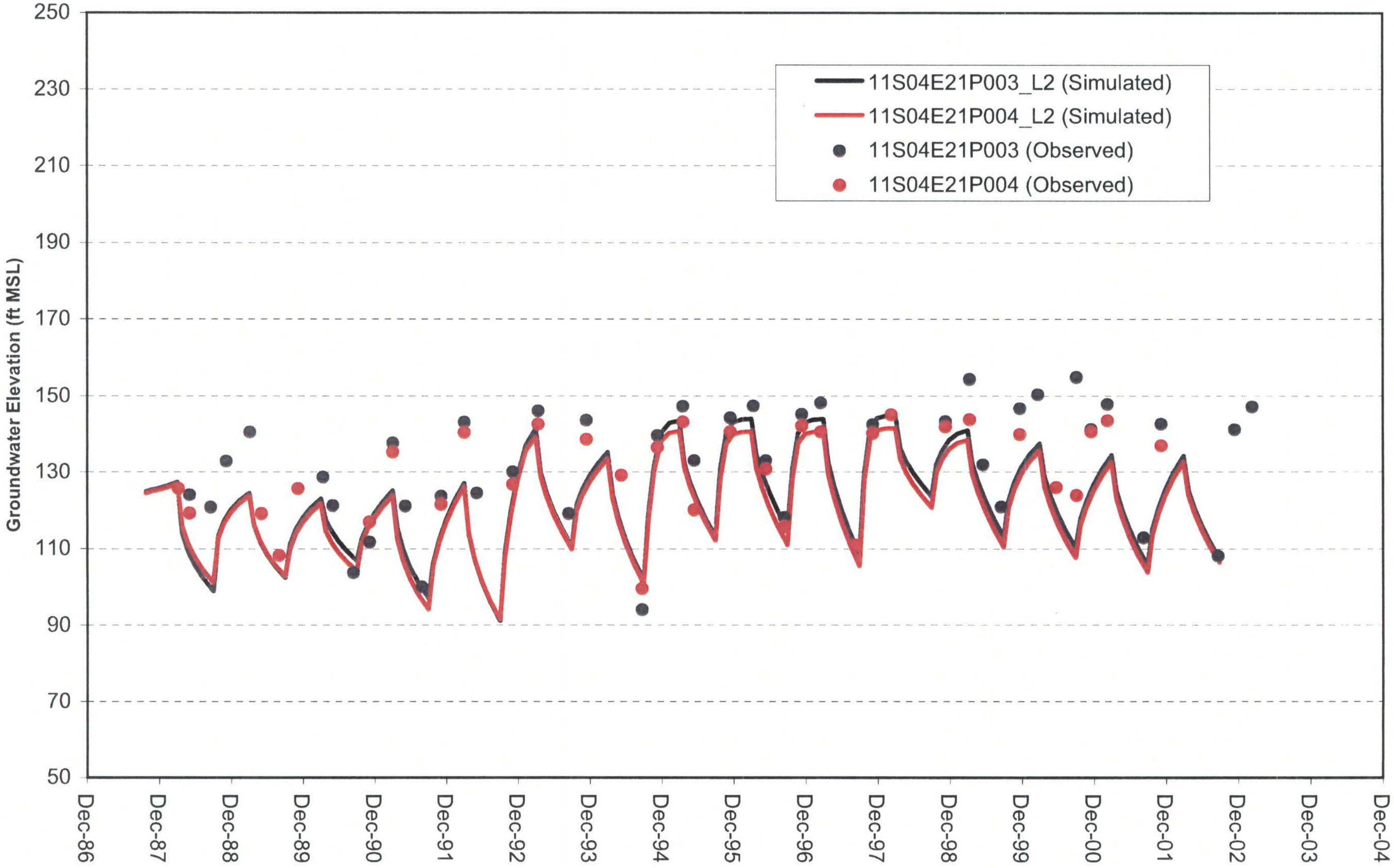


R133 Results.xls

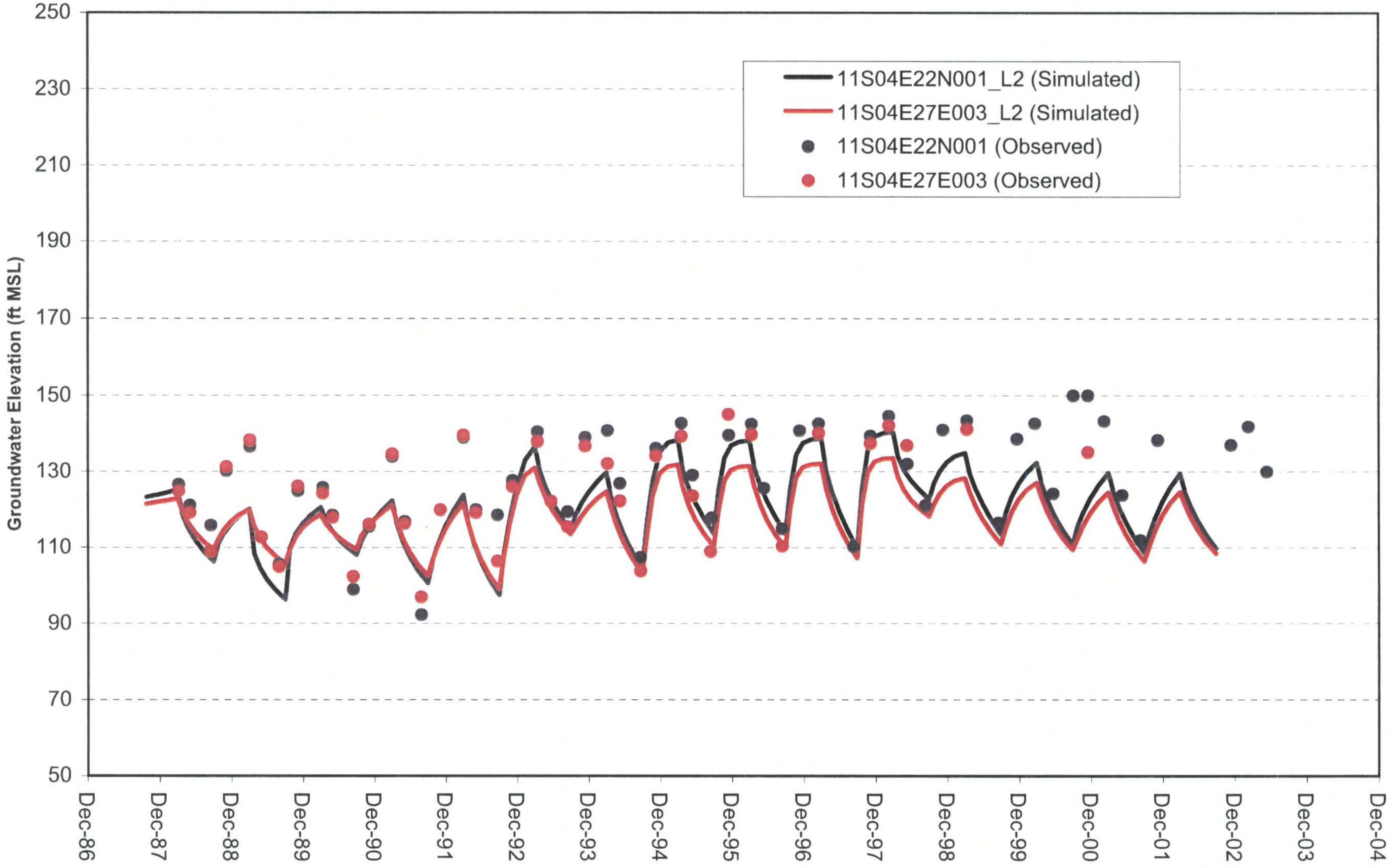
Simulated versus Observed



Simulated versus Observed



Simulated versus Observed



R133 Results.xls

APPENDIX D

Appendix D
Alternative Calibration

APPENDIX D

Alternative Calibration

It is conceptually reasonable to assume that Llagas Creek may recharge groundwater in winter months during excessively wet periods similar to those experienced in the basin during the mid-1990s. Recharge to groundwater during these periods is a distinct water budget component, separate of intentional groundwater recharge during the same periods. This concept was tested in the model by adding a 1-foot stage to the unconfined reach of Llagas Creek in winter stress periods when the areal recharge in the basin exceeded 3,000 acre-feet. This infers that significant deep percolation from the stream only occurs during wetter periods. Separate simulations with a 1-foot river stage were performed using values for uniform Layer-1 specific yields of 10 percent, 5 percent, and 3 percent. Though the model no longer matches the short-term water level fluctuations as well as before due to seasonal pumping, the basin's long-term response is reasonably represented (Figures D-1 through D-3). Increasing specific yield using this concept also decreases flow to drains (Figures D-4 through D-6). A specific yield value of 10 percent is a more reasonable "long-term" value for a regional aquifer system. Use of this value is more appropriate for long-term (year or more) simulation of basin response. The smaller values are appropriate for shorter-term events like pumping tests or seasonal responses.

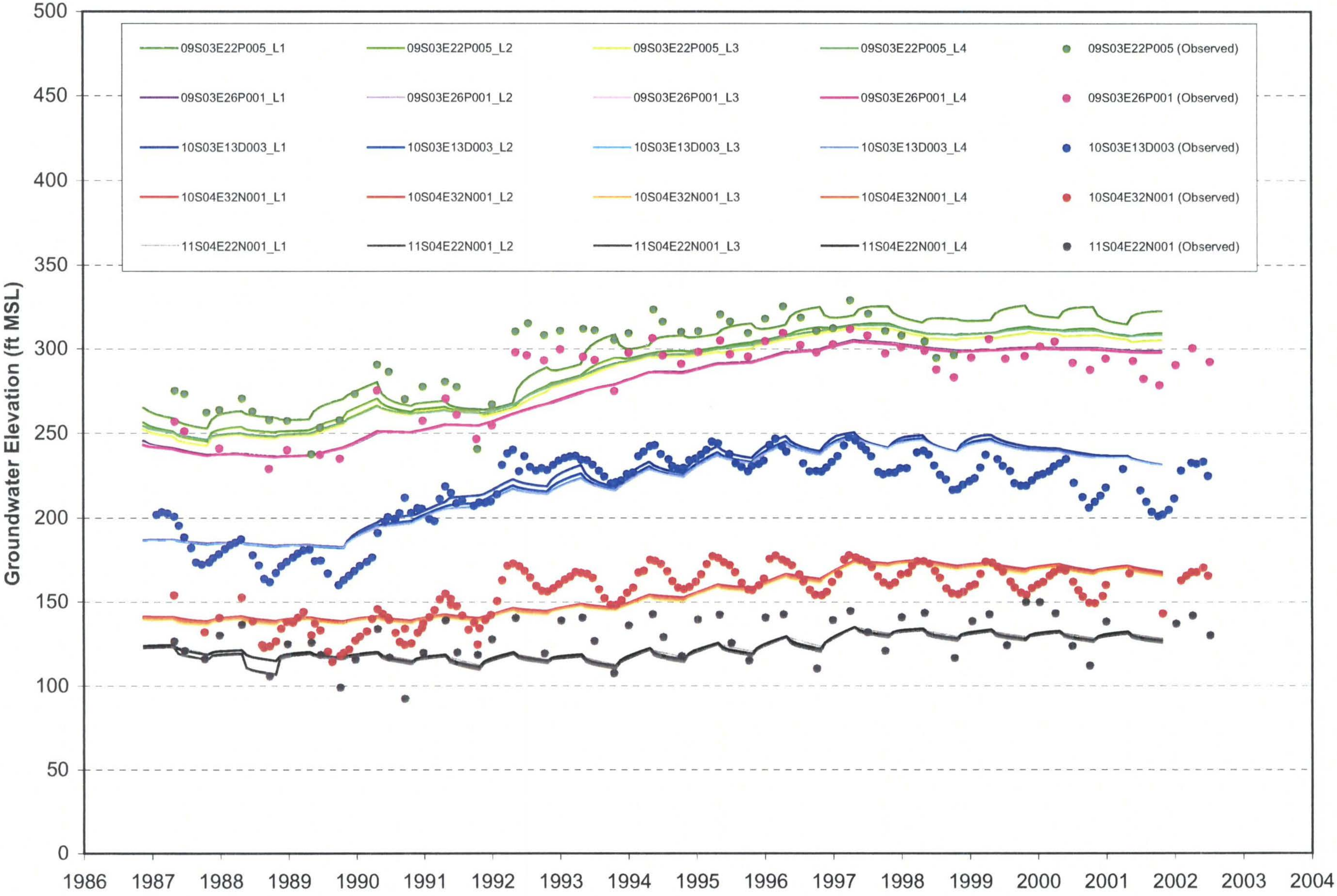


FIGURE D-1
CALIBRATION HYDROGRAPHS
SPECIFIC YIELD = 10%

R064 Results.xls

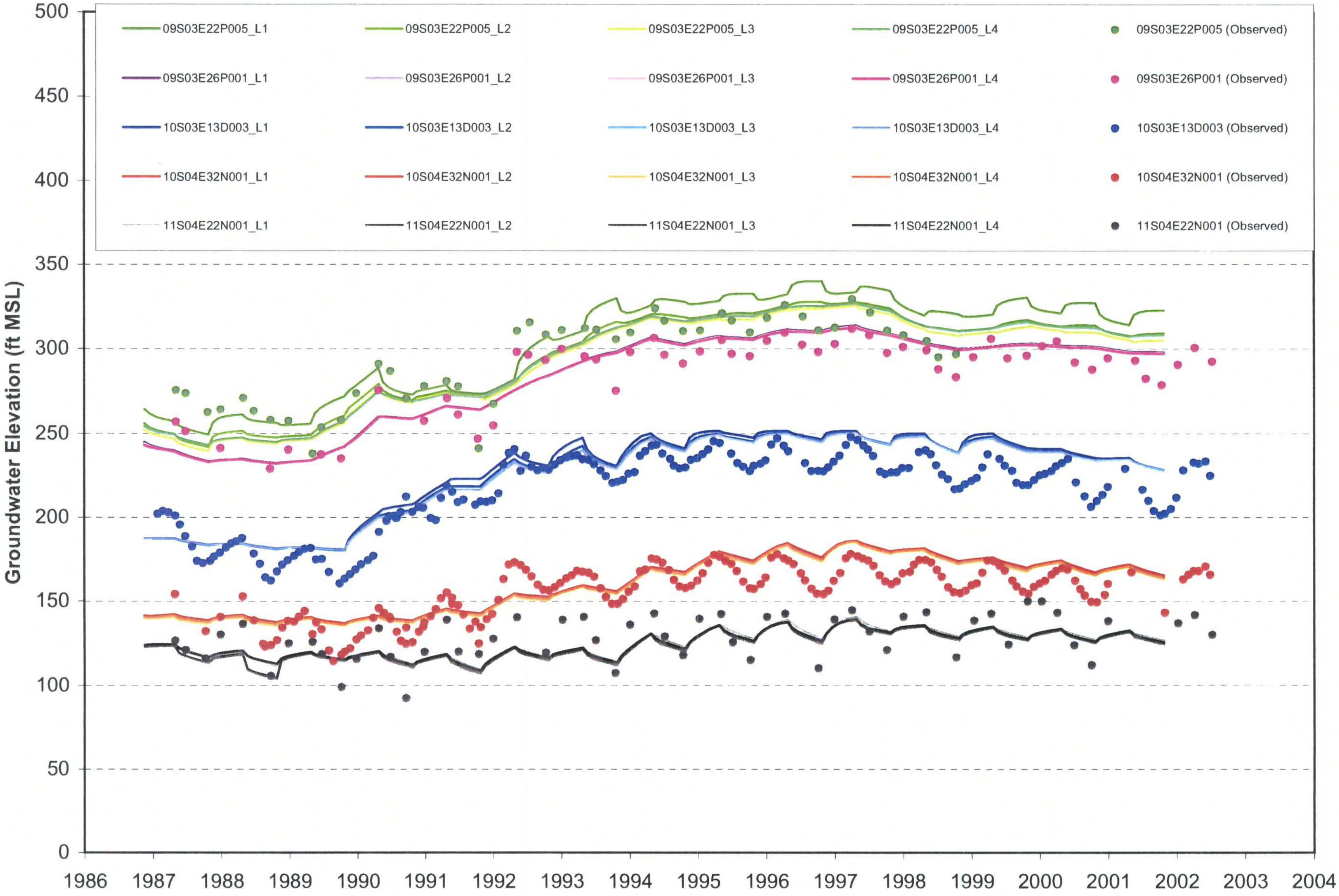


FIGURE D-2
CALIBRATION HYDROGRAPHS
SPECIFIC YIELD = 5%

R063 Results.xls

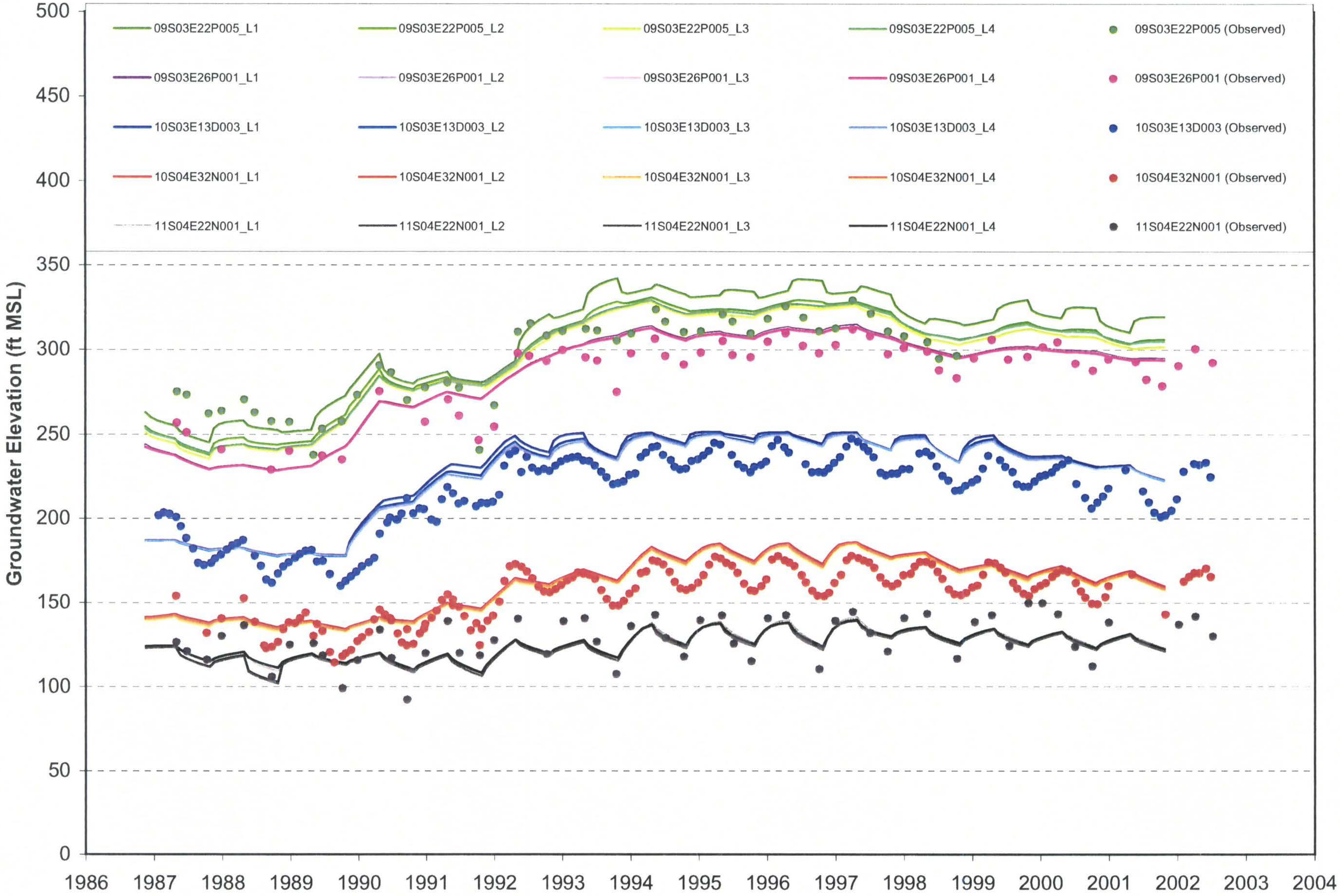


FIGURE D-3
CALIBRATION HYDROGRAPHS
SPECIFIC YIELD = 3%

R065 Results.xls

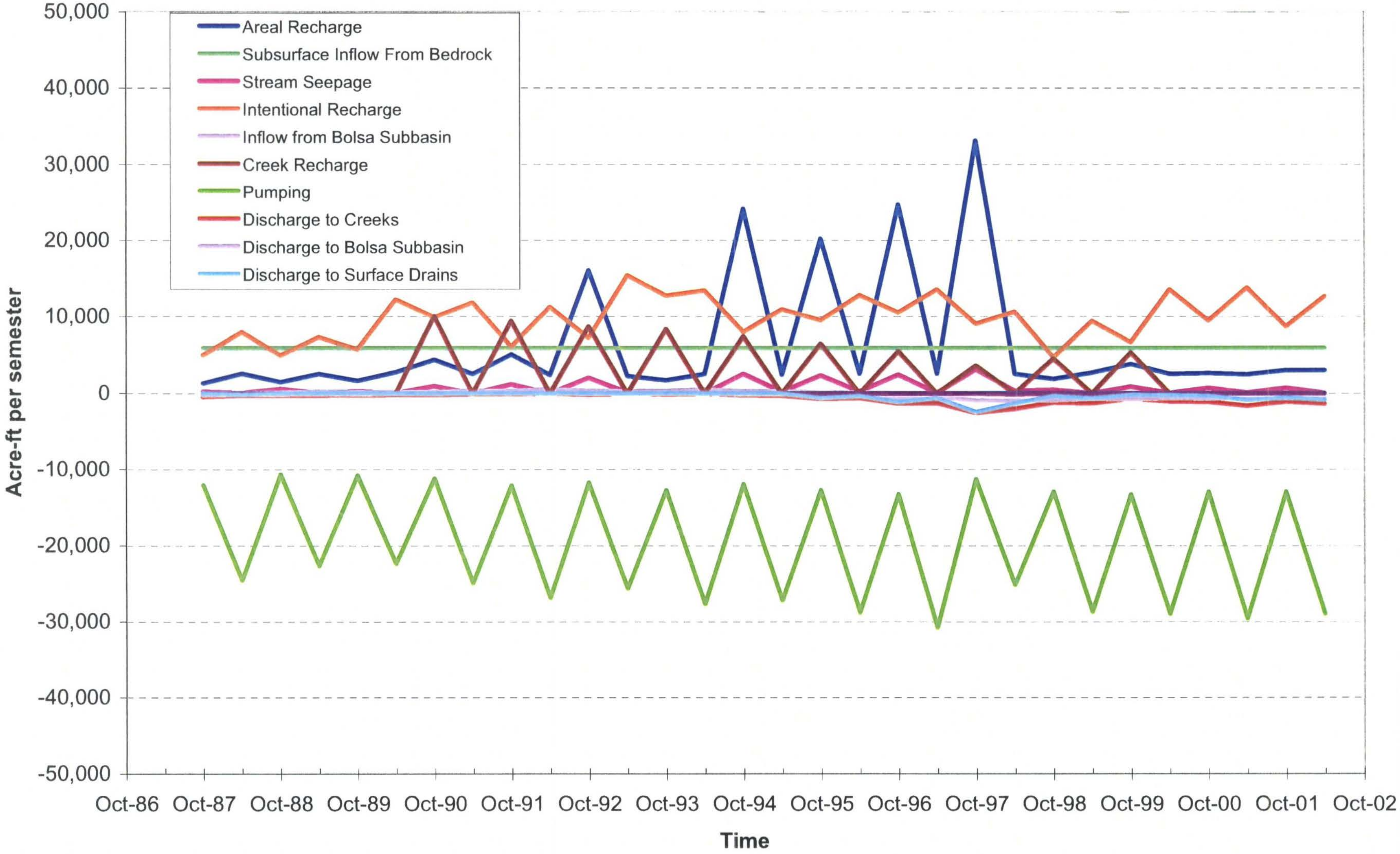


FIGURE D-4
SIMULATED WATER BUDGET COMPONENTS
SPECIFIC YIELD = 10%

R064 Budget.xls

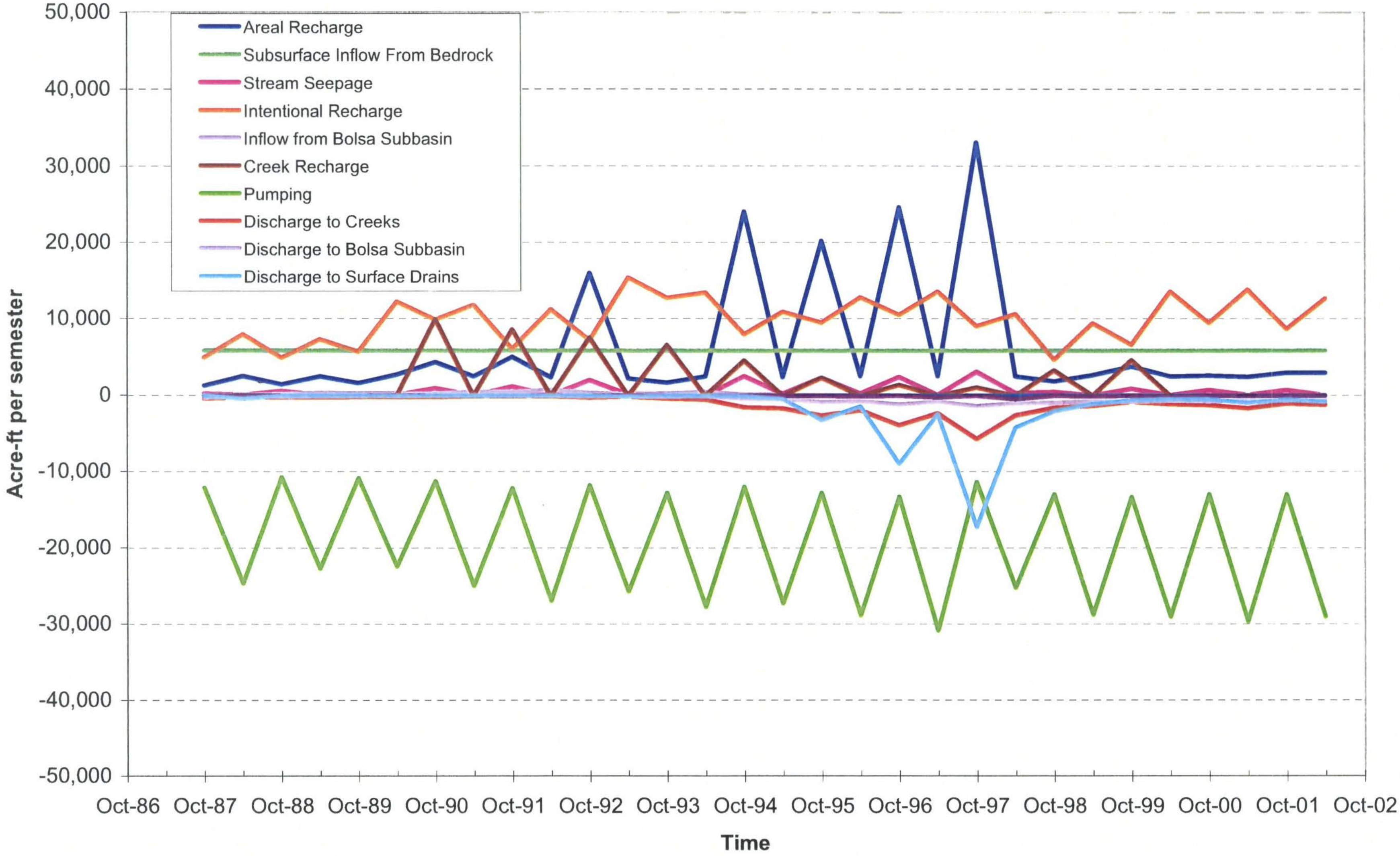


FIGURE D-5
SIMULATED WATER BUDGET COMPONENTS
SPECIFIC YIELD = 5%

R063 Budget.xls

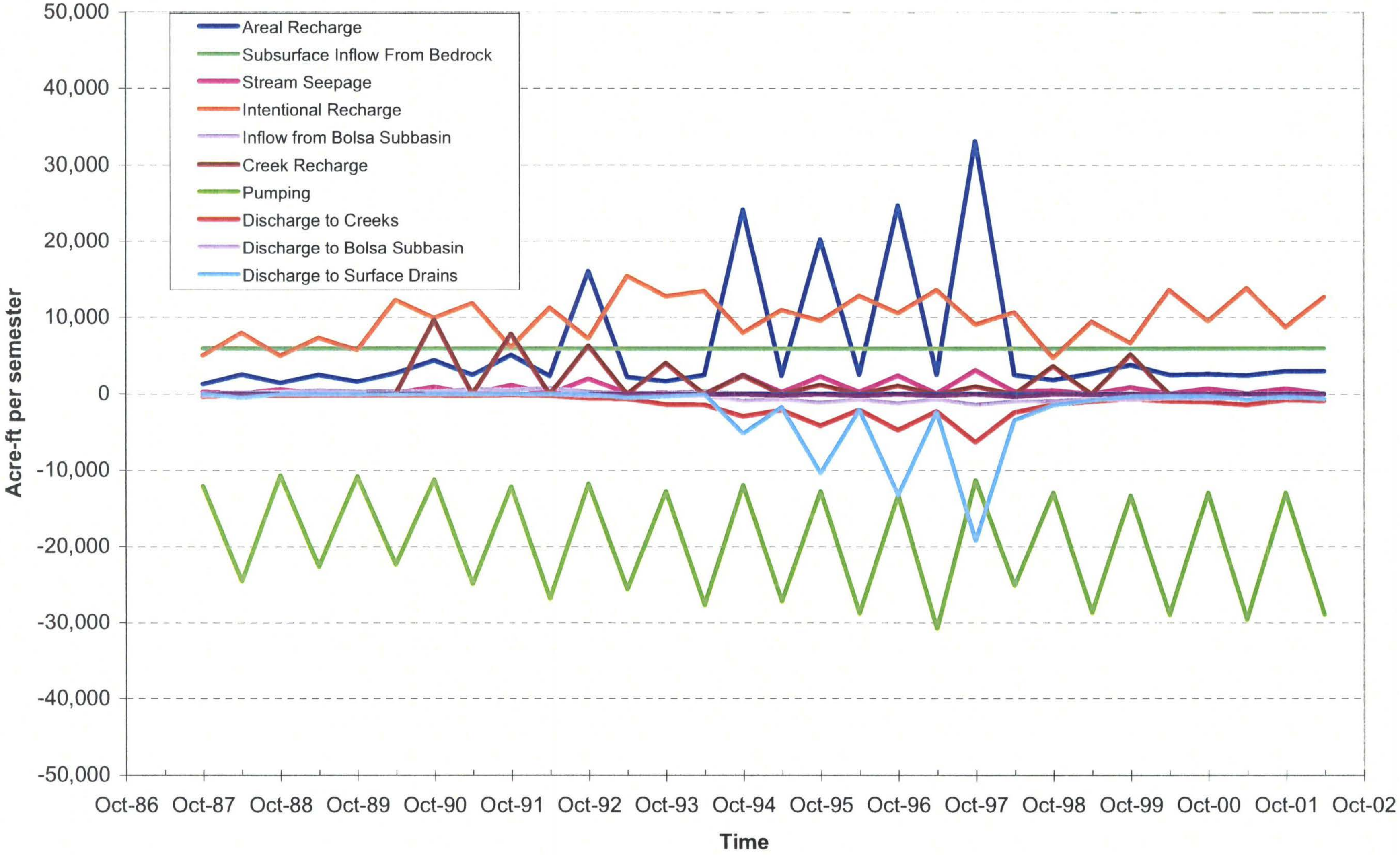


FIGURE D-6
SIMULATED WATER BUDGET COMPONENTS
SPECIFIC YIELD = 3%

R065 Budget.xls